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ARDEC ELECTRIC GUN IN-HOUSE TEST PROGRAM ANNUAL REPORT, FY 88

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This report summarizes the experimental testing conducted on three railguns during FY 88 at the ARDEC Electric Gun Facility. It discusses improvements to the 30-megajoule homopolar generator and 250-kilojoule capacitor bank as well as instrumentation techniques and analysis capabilities. It also describes the planned high energy lab. The 50-mm square bore railgun demonstrated dramatic improvements in barrel wear with solid armatures of proper design. Tests on the short prototype of the 20-mm round bore railgun indicated that the composite structure will withstand the forces involved in the upcoming 5 km/sec tests using plasma armatures. The 50-mm round bore railgun short prototype tests pointed out the difficulties of designing solid round bore armatures and the importance of matching barrel stiffness and armature compliance.

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CONTENTS

INTRODUCTION

Mission

The ElectroMagnetic Armaments Technology (EMAT) Lab was established in 1981 as the Army's center for test and development of electric gun propulsion. This lab provides a national testing facility for independent evaluation of hypervelocity electric gun components and systems.

Merits of In-House Projects

The in-house experiments are making exciting progress in optimizing railgun barrels and projectile armatures. Energy efficient, low voltage drop, solid armatures will result in smaller power supplies and longer wearing gun barrels. Compliant solid armatures will permit low cost barrel structures. Plasma armatures are being explored for very high velocity guns because of the problem of maintaining sliding contact at these velocities. Plasma drive experiments will evaluate stiffness and strength requirements of cast composite barrels under high bore pressures.

CAPABILITIES AND RESOURCES

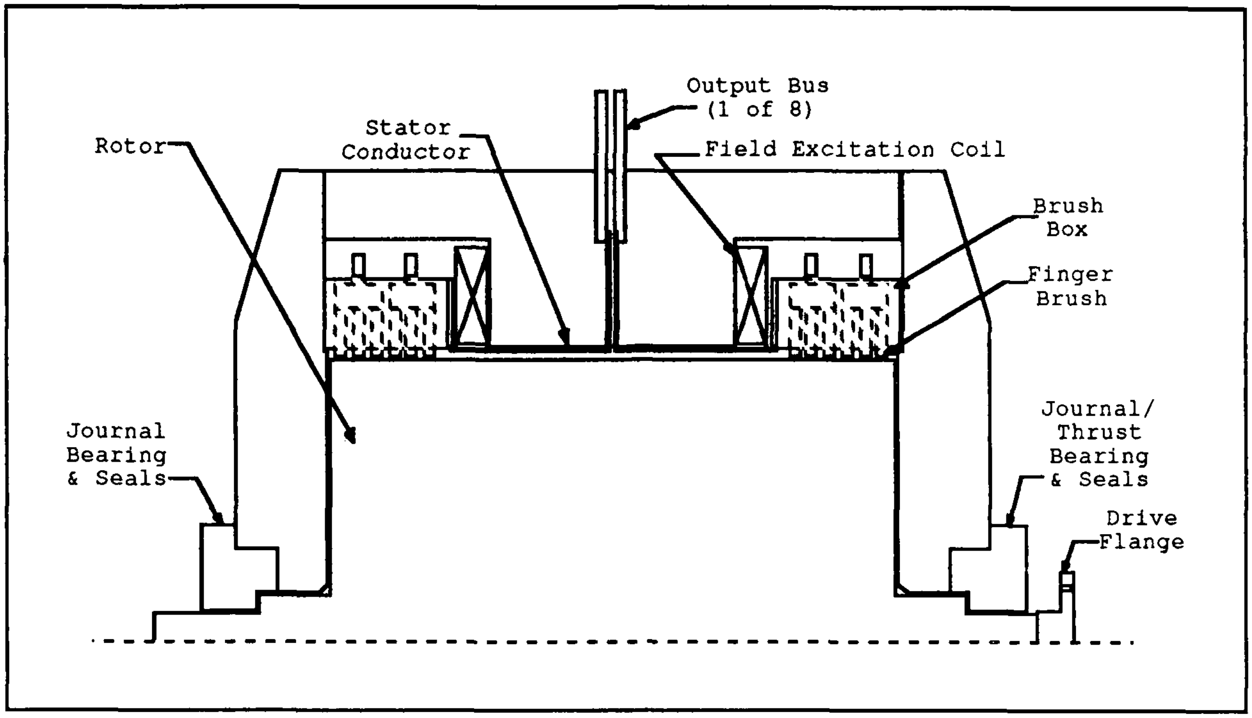
The existing ARDEC facility includes a 30 megajoule (MJ) homopolar generator (HPG) with a 4 microhenry (μH) energy storage inductor capable of producing 1.3 megamperes (MA), and a 250 kilojoule energy storage capacitor bank capable of producing 0.5 to 0.9 MA with power conditioning equipment. There is also a sophisticated 40 channel automatic data acquisition and control system, and a 150 kilovolt and 1 megavolt flash x-ray systems for projectile in-flight radiographs.

Work is underway for a high energy lab in an adjacent building utilizing a 65 MJ capacitor bank.

Homopolar Generator (HPG)

Characteristics

The HPG is a truncated-drum type generator, using an all-steel rotor, with a diameter of 25.125 inches, and a length of 24.3 inches. Machined from a single billet of a custom, high nickel, alloy steel, it stores 30 MJ inertially at a speed of 8300 revolutions per minute (rpm) (277 meters/second tip speed). An externally excited field coil is located within the HPG housing, and is capable of providing air gap field densities of 1.6 Tesla at an excitation of 1800 Amperes. Output current is extracted by a system of 3600 finger brushes, in brush boxes which contain 60 brushes each, as well as the bladders which lower the brushes to the rotor surface. Current is conducted out of the machine on a drum type stator conductor, which provides a discharge path concentric with the rotor. The current exits through eight busbar pairs, located at the axial center of the machine, providing for easy management of the bursting forces and minimization of the inductance of the machine. Figure 1 provides an overview of these components.



HPG Cross Section
Figure 1

Changes

During the past year, a number of upgrades have been made to the HPG and its subsystems. The most noticeable change is the replacement of the original 100-hp drive motor with the 320-hp motor, speed increaser, and overrunning clutch system .

The prime reason for the installation of this more powerful system is the decrease in the time required to spin-up the rotor. The original drive motor lacked the startup torque to overcome the static friction in the rotor support bearings. This necessitated turning the rotor over by hand, using a large wrench, while simultaneously starting the drive motor, to being the rotor spin-up process. Once the rotor had begun to turn, times in excess of 25 minutes were required to reach the maximum operating speed of 6500 rpm. This long spin-up caused substantial heating of the journal bearings supporting the rotor. To illustrate, 50-mm square bore railgun shot #9 was to be a 1.3 MA discharge, requiring that the HPG be motored to 6500 rpm. The spin-up required almost 27 minutes, with the drive end bearing (which contains the thrust bearing) seeing ΔT=43°C, and the switch end bearing seeing ΔT=35°C. The new drive motor will propel the rotor to a maximum speed of 8300 rpm, in under 10 minutes. This will decrease the heat generation in the bearings, and reduce the risk of operating the machine correspondingly. Also installed, along with the new drive motor, is a new 750 KVA (34.5 kV to 480 V) substation to provide the approximately 800 A line power requirement for the new motor.

The lubrication system has also been upgraded to handle the increased rotor speed capability. New main and backup pumps and drive motors have been installed to provide increased flow rate, up to 23 gallons per minute, and to replace the older units which were in poor condition mechanically. The backup pump drive has been increased to a 220 V unit, and the auxiliary generator rewired for 220 V operation.

The brush actuation system has been thoroughly rehabilitated. The actuation system has had all components between the programmable logic controller (PLC) and the brush drop valve redesigned and replaced, with an eye towards increased reliability and noise immunity.

The final area of improvement is in the control system itself. All cabling between the PLC and the field devices has been traced, connections have been verified and tightened, and most importantly, properly grounded. This ensures that the system will be as noise immune as is possible, in what is inherently a very noisy environment. The relay ladder logic program and the BASIC operator interface programs have all been rewritten to provide more information to the operator during tests, and for more accurate monitoring of the HPG parameters during a test. Currently being evaluated are hardwired control interfaces for the most important machine parameters. These units will supercede the PLC in the control hierarchy, to ensure that software errors will not cause damage to the machine, or personnel injury.

Prime power is provided by a 320 hp, variable speed DC motor, driving through a 1:2.54 speed increaser and overrunning clutch. Conventional, oil-lubricated hydrodynamic bearings are used to support the rotor, while any unbalanced magnetic forces are taken up by a double-acting hydrodynamic thrust bearing at the drive end of the machine. The lubricating oil is provided by a high volume system incorporating thermostatic control of the lubricant, and a redundant supply, powered by a 7.5 kilowatt (kW) auxiliary generator, to ensure that the bearing oil supply will not be compromised by a loss of line power.

When used in conjunction with the toroidal, Bitter plate 4μH inductor, and associated buswork, the HPG is theoretically capable of 1.9 MA discharges. This assumes a rotor speed of 8300 rpm, with a field current of 550 A and an external circuit resistance of 38 $\mu\Omega$, and yields a time to peak of ~156 ms. Data currently in hand points to the belief that increasing the field current beyond 550 A will not increase the output voltage of the HPG, due to saturation of the steel rotor, and will cause increased ohmic (I^2R) heating of the field coils. While the field coils are water cooled, the added heat load is, nonetheless, undesirable.

While the theoretical 1.9 MA peak current may easily be calculated, the actual peak current of the HPG is somewhat lower. Analysis of the limits of the machine components has shown that the rotor will fail structurally at 1.48 MA. At that point, the stresses at the rotor surface, due to thermal and rotational effects, will equal the yield strength of the material, Sy=827 megapascals (120 kilopounds per square inch). A factor of safety of 1.2 allows operation at a peak current of 1.32 MA, and this is considered to be the peak operating current at this time. The current limit of the stator conductor is 2.1 MA, and that of the brushes is 3.2 MA, so these components are operating in safe current regimes at all times.

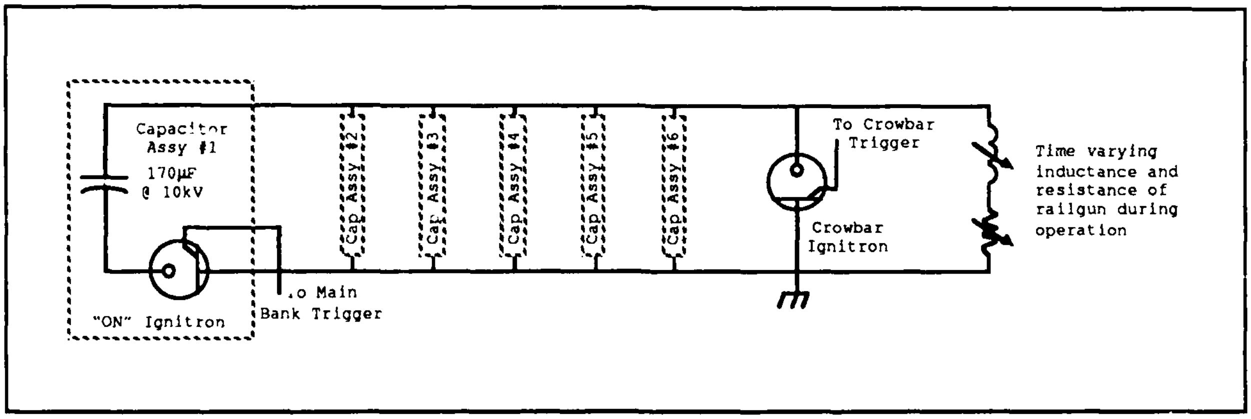
Operation of the HPG is controlled by a GE Series Six Programmable Logic Controller (PLC). The PLC provides the ability to monitor a variety of digital and analog inputs, and control digital and analog outputs, at a rate of approximately 100 scans per second. The relay ladder logic programming controls the operation of the HPG and the drive, field, lubrication and brush drop subsystems during the launch cycle. A BASIC program provides for the operator interface, and passes input parameters to the PLC to describe the type of test to be run, the rotor speed, etc.. Currently there are programs written to test the drive motor, the field excitation supply, the brush drop system, and various combinations of these subsystems for open circuit, short circuit and railgun tests.

The ladder logic continually scans the input channels and is programmed to abort the test being run if any of the inputs stray beyond a preset limit, eg, lube oil pressure below a minimum value, or bearing overtemperature. In normal operation, it controls the spin-up of the HPG rotor to a preset speed (to be determined by the current level required for the test to be run), actuation and verification of excitation field, and energization of the brush actuators. Additionally, should a fault occur, the cause of the failure is reported to the operator.

CAPSTAR

Characteristics

Five separate individual capacitor banks are connected in parallel to a central output plate to make up the 250 kJ pulse power supply for smaller experiments. Storing 50 kJ each, at 10 kv, the capacitor banks are remotely controlled from a master control panel, and have separate charging and switching subsystems. The outputs of each bank can be conditioned with either inductors or current transformers to be capable of producing from 0.5 to 0.9 MA, with various pulse lengths. Generally speaking, the pulse length shortens as the peak current increases. Ignitrons are used to initiate the discharge pulse, and to crowbar the capacitors when peak current is reached. Figure 2 is a generalized schematic of one capacitor bank.



50 KJ Capacitor Bank
Figure 2

This allows the discharge pulse to be extended, since the time constant, τ, of the circuit, is now L/R, rather than RC, and an exponential decay may be expected, rather than the sinusoidal discharge characteristic of an RC circuit.

An additional benefit is the increase in capacitor life. Since the capacitors are removed from the circuit at peak current (when voltage has dropped nearly to zero), the voltage reversal the capacitors experience is minimized, thus increasing capacitor life from ~15,000 shots at 50% voltage reversal to >100,000 shots with a 10% reversal.

Changes

Bank Metering. The capacitor banks being used were originally designed for use in an industrial environment, where metering and control systems are not expected to operate with the precision required of a research program. There have been a number of problems experienced in determining the actual charge voltage of the banks. This information is an absolute necessity in determining bank performance during railgun experiments. Of particular importance is ensuring that all banks are charged to the same voltage. Failure to do so entails the possibility that a given bank may drive some part of its discharge current into another bank, rather than the load. While the isolation provided by the pulse transformers or solenoidal inductors in use will minimize this "current sharing", it contributes to inefficiencies and, as only 250 kJ are available to begin with, that is to be avoided if possible.

To this end, the metering systems have been upgraded from those originally installed by the manufacturer. The factory-installed metering system used a voltage divider which was directly connected to the panel meters at the control console through some simple signal conditioning circuitry. In this configuration the potential for a number of problems existed. The first is a personnel safety question. Should the voltage divider break down, bank voltage would be present within the control console. While there has never been an occurrence of this nature, the possibility is there, and should not be ignored. The second is a lack of precision in the meter circuitry, as it was designed and installed. The layout of the original metering systems leads one to believe that economy and speed in design and fabrication were the primary drivers in that project.

In order to provide more accurate, reliable and safe bank metering, custom Analog to Digital (A/D) and Digital to Analog (D/A) circuitry has been designed and is in fabrication. These devices use optical isolation to provide personnel isolation from 10 kV bank voltages, and a Pulse Width Modulation technique to transmit the signals over cable to the control console.

Ignitrons. Another problem area within the capacitor banks has historically been the ignitrons used for forward and crowbar switching. Ignitrons are mercury vapor switches, which operate, electrically, in much the same fashion as thyristors or SCRs. The prime reason for the use of ignitrons in this sort of an environment, rather than an SCR, is their ability to effectively switch high currents without damage. There are drawbacks, however. The ignitrons are vacuum tubes, and have glass seals, with poor mechanical strength. The ignitor pins, which operate in a fashion similar to that of the gate on an SCR, can become wetted with mercury and fail to generate the vapor required for the switching event to occur. Also, the anode pin may become wetted as well, leaving the ignitron in a shorted state.

There are no simple solutions to the problems above, short of replacing the ignitrons with switches of another type. Unfortunately, there are few alternative technologies which provide for the same speed and current carrying capability. The procedure developed then, is to test ignitrons before each high energy discharge (above 6 kV bank voltage). The ignitor and anode pins are tested for resistance to ground. If any are found to be below nominal value, a high current source is connected to that pin to try to evaporate the mercury. If that fails the ignitron is replaced and shipped off-base for reconditioning.

Instrumentation

Data Acquisition System

The EMAT Branch has recently upgraded its data acquisition equipment and has rewritten the software that controls the acquisition, retrieval and analysis of laboratory test data.

For several years, the Branch has relied upon a Digital Equipment Corporation PDP-11/34 computer system, supported by Tektronix SPS BASIC software, to run its Tektronix 390AD digitizers. Unfortunately:

1. The limited memory of the PDP-11/34 made expansion of the software impossible.

2. Obsolete architecture made expansion extremely expensive.

3. The reliability of the disk drives and tape backup had decreased substantially in recent years, making data archival risky and maintenance expensive.

This year, PDP-11/34 was replaced by IBM PC AT computer equipped with one 30-megabyte hard disk drive, a 60-megabyte tape backup unit, and three GPIB (IEEE-488) controller boards. In addition, the ASYST data acquisition and analysis software was obtained.

ASYST is a FORTH-based language with many high-level procedures that make data acquisition programming particularly easy to perform. ASYST permits a knowledgeable programmer to write a complete data acquisition application, including menus, data manipulation capabilities, and graphics. The software has been written in the ASYST language by an inhouse engineer and its currently in use.

Thirty two additional digitizer channels, manufactured by DSP Technology and made to the Computer Automatd Measurement and Control (CAMAC) standard for high-level interface, will be incorporated along with existing 40-channel data acquisition system. The original supporting software was written in a Pascal by DSP Technology but it's being rewritten again in an ASYST language to ensure compatibility. When the rewriting process is finished by DSP Technology, the software will be incorporated along with the in-house supporting software.

Diagnostic Tools

Pre-shot measurements. Projectile insertion force is measured with a load cell which is comprised of a beam-loaded strain gauge and a 12 volt power supply. This apparatus gives a direct output of force measurement via a digital voltmeter.

Performance measurements. There are basically three important performance measurements of great significance. These are current, voltage, and projectile velocity.

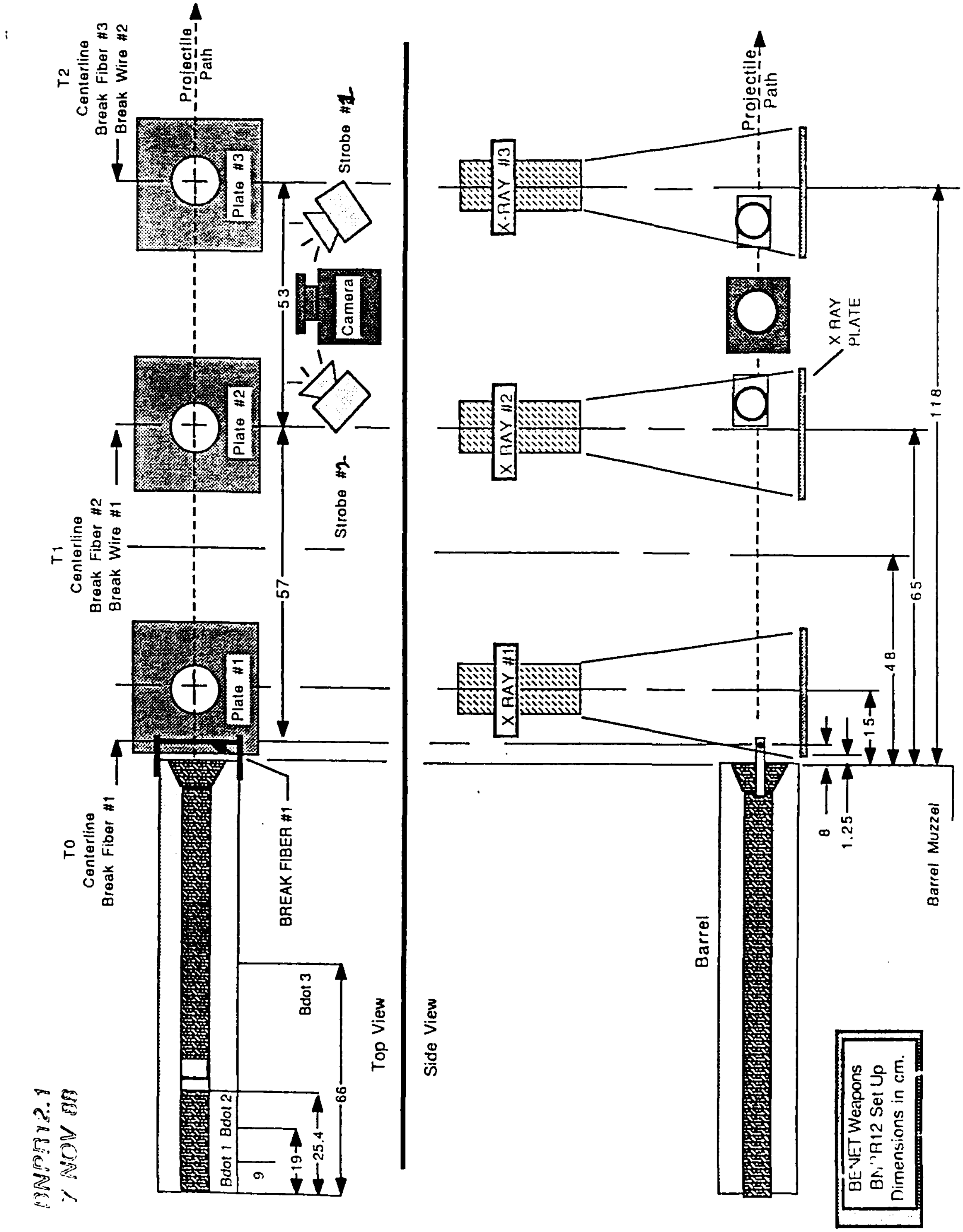
All current measurements are done with Rogowski coils. A Rogowski detects the magnetic field that is proportional to the time rate of change of current (di/dt). This may be scaled directly to di/dt or integrated by means of passive integrator, active integrator, or numerical integration and scaled to current. Previous Rogowskis from T&M Devices with different calibration factors have been replaced by the Rogowskis made from the Los Alamos National Laboratory, which have almost an identical calibration factors for consistancy.

Voltage measurements are performed using either resistive voltage dividers or current transformers measuring current through a known resistance. We have replaced our voltage dividers previously but decided to replace them with Pearson current transformers with a precision resistors for a more accurate measurement and also for a better isolation between the experiment itself and the measuring instruments.

In-bore velocity is measured with the magnetic pick-up coils (B-dot coils). Muzzle velocity measurements are performed by break-wire and break-fiber position sensor methods. Each method consists of electronic circuitry which gives an output when a wire or fiber is broken by a projectile. The break-fibers are also used as a trigger source for the flash units of open-shutter polaroid camera and the flash x-rays (Figure 3). Both camera and flash x-ray give a picture of a projectile in flight.

Other measurements. When a projectile is initially accelerated by gas injection, the injection pressure is measured with a pressure transducer. The acceleration is measured with an accelerometer mounted on the projectile itself. The signal is collected via fine wires running from the projectile out the muzzle to the data acquisition system.

Post-shot measurements. A pictorial documentation of barrel bore erosion is obtained by the use of a 14-mm borescope and a 35-mm camera. Bore diametral displacement is measured by a gage using a linearly-variable, displacement transformer (LVDT) with a sensitivity of 0.1 v/ 0.001 in. In addition, photographs of the projectiles are also taken.



50-mm Round Bore Diagnostic Set-up
Figure 3

Analytical Support

General

In addition to experimental capabilities, the ARDEC EMAT lab has strong analytical capabilities. Ongoing analytical research projects include electromagnetic and mechanical analysis of an augmented railgun and study of high velocity impact phenomena. In support of these analytical efforts, the EMAT lab has acquired or written several codes, including railgun simulations, a general purpose finite element code (ANSYS), a large deformation finite element code, a solid modeler (PATRAN), and a surface modeler (SURFMODL).

Specific

Impact data from the 50-mm square bore railgun will be used to verify the model being developed to study segmented penetrators.

New Simulations Hardware

A Silicon Graphics Iris 4D-70GT engineering workstation, two Iris 3020 workstations, and one Iris 3130 the branch provide outstanding computational and graphics presentation capability. The workstations are used for finite element analysis, solids modeling, and computer-aided design.

Electromechanical Finite Element Modeling

ANSYS is a general-purpose *finite element* code employed by the EMAT branch. Running on the Iris workstation, ANSYS provides an invaluable tool for gaining insight into complex current-carrying configurations, in addition to filling the more traditional role of a mechanical stress solver. Two broad classes of problems are currently being investigated by the branch using ANSYS.

The first is failure analysis of EM projectiles under setback loading. The estimated acceleration profile for the projectile (predicted with other, specialized circuit simulation programs) can be entered into ANSYS for non-linear dynamic analysis. Stress levels in the projectile and its composite-material sabot can be accurately predicted to aid in important design decisions.

The other application of ANSYS is in determining the structural containment required for a particular railgun barrel geometry. Using the finite-element preprocessor, a model of the barrel in question is constructed with material properties, current density in conductors, and magnetic boundary conditions specified by the analyst. The program solves for magnetic vector potential, from which the corresponding magnetic flux density (B-field) is determined. The interaction of B-field and current produces Lorentz forces on the conductor, which the program calculates and uses as a load for subsequent stress analysis. Thus the stresses in the conductor and the surrounding support structure may be found. The entire process is accomplished in one solution step.

Penetration Simulations

The EMAT branch employs the EPIC-2 (Elastic-Plastic Impact Calculations in 2 Dimensions) finite element code to simulate high-velocity impact of novel penetrators to evaluate effectiveness. EPIC-2 differs from most general-purpose finite element codes because it uses an explicit approach to solving the equations of stress and strain. This allows the solution of large-strain problems without reformulating and inverting a stiffness matrix in every cycle, which in turn allows long problems (thousands of cycles) to be run without requiring excessive computational resources.

EPIC-2 uses a Lagrangian formulation (in which the grid distorts with the material). In a large-strain impact problem, this can cause inaccuracy in the solution and excessive computation time (because the time step size is controlled by the smallest element in the problem). EPIC-2 solves the grid distortion problem by selective pruning, in which elements are dropped out of the problem as they reach a failure criterion. At that time, the nodal masses are retained to conserve energy, but the elements lose all their material strength and can sustain no pressures. With algorithms to automate it, this process is commonly referred to as "erosion". Erosion in EPIC-2 usually only occurs at a material interface, which is preserved by a general-purpose "slideline" that transmits forces across the material boundary and allows relative slippage of the two materials.

EPIC-2 has been used extensively for penetration calculations in the EMAT branch for over three years, and is running on the branch's Iris workstations. Recent laboratory tests conducted in the EMAT laboratory at ARDEC have shown EPIC-2's hole profile predictions to be accurate to within 10 percent. It has proven to be a very useful aid in novel penetrator evaluation.

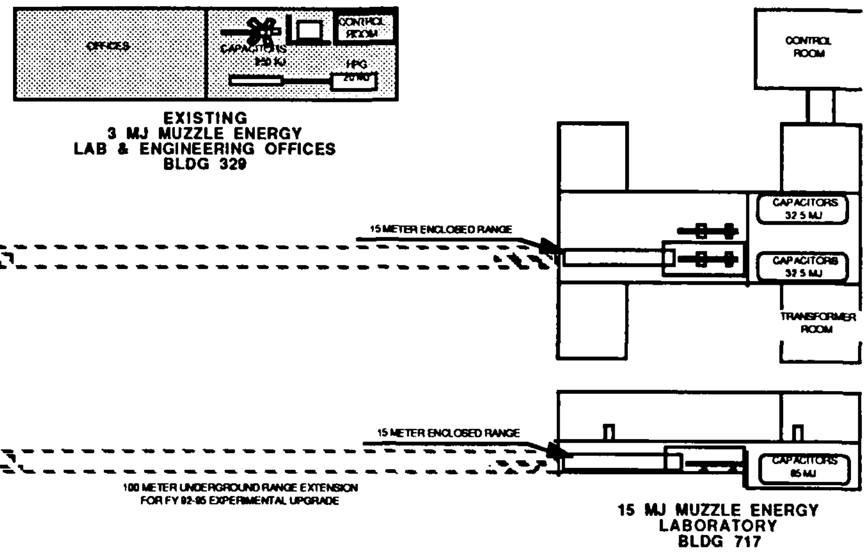
Solids Modeling

The branch recently acquired the Ballistics Research Laboratory computer-aided design ray tracing system for use on its Iris workstations. Engineers are investigating use of the package for concept development and electromagnetic signature analysis.

Planned High Energy Lab

ARDEC is constructing an advanced, high energy, electric gun test facility in Bldg 717 (Figure 4). This facility will serve as a workhorse test bed for a variety of electrothermal (ET) and electromagnetic (EM) launchers.

Maxwell Laboratories, San Diego, CA will provide a modular 65-MJ, capacitor-based, pulsed power supply with twenty individual modules, operating at 24 kilovolts, capable of storing 3.25 megajoules apiece. Individual buswork runs from each module will be provided so that flexibility in configuration is ensured. High power coaxial cable connections will link the buswork to the launchers. Each of the twenty modules may be switched in or out of the circuit, depending upon the energy levels and voltages required for the experiment under consideration. Modules may be "ripple fired" to extend the period of the discharge, if that is desired. A comprehensive



ARDEC Electric Gun Laboratory Facilities
Figure 4

system of keyed interlocks will be installed to provide for personnel safety during bank operation. Pulse forming networks have been designed to provide appropriate pulses for both ET and railgun loads.

FMC's Advanced Systems Division, Minneapolis, MN will provide a 120-mm ET launcher. Using a modified M256 smoothbore gun tube, which may be fired in either the pure ET configuration, or a Combustion Augmented Plasma (CAP™) mode, this launcher will deliver muzzle energies in the 9 megajoule regime – 2.8 kilograms at 2.5 kilometers/second. FMC will also provide the enclosed gun room, 10-meter free-flight range and target room for the facility. All of these are designed to withstand both the normal blast overpressure from a launcher of this type, as well as the overpressure from a gun tube or breech failure, without compromising the structure of Bldg 717.

Sparta, Inc, San Diego, CA, will provide a 90-mm EM railgun for this facility. This gun will provide 9–11 megajoule muzzle energies with projectile velocities of 3 kilometers/sec. The barrel has a hydraulically-prestressed bore for maintaining stiffness during firing and to allow replacing bore materials.

A 900-square foot control and data acquisition center will be EMI/RFI shielded to provide for protection from induced signals due to the experiment itself as well as TEMPEST protection. All power to the control center will be filtered and UPS protected, while control and data acquisition signals will be carried over fiber-optic links, thus ensuring secure transmission, in an environment free from ground loops.

Longer-term plans are underway to affect the extension of the 10-meter free-flight range for an additional 100 meters. This project, requiring tunnelling under Picatinny Peak, will provide a secure facility for the testing of classified as well as "ordinary" hypervelocity kinetic energy rounds.

EXPERIMENTAL RESEARCH

Several accelerators have been built and fired, and are available for the purpose of evaluating materials and gun-system components. The accelerators include large (50 mm) square- and round-bore railguns, and small (10 mm and 20 mm) square- and round-bore railguns.

50-mm Square-Bore Railgun

Characteristics

The 50-mm square-bore railgun (Figure 5) is a bolt-together railgun 2.65 meters long with copper rails backed by G11 fiberglass and steel plates. The rail cross section is 50.8 mm x 19.05 mm with a 50 mm spacing which yields an inductance per unit length (l') of 0.4 μH/m. The electrical schematic is shown in Figure 6.

A modified opening rail switch was used for these tests. The shuttle had drop-in brushes to reduce the turn around time. The pnuematic-hydraulic release mechanism was replaced with a shear pin. Each shear pin was calibrated to break at 80% of maximum test current for each test.

The inductor was modified with substantial aluminum support structures to eliminate the movement of the Bitter plates experienced in previous tests.

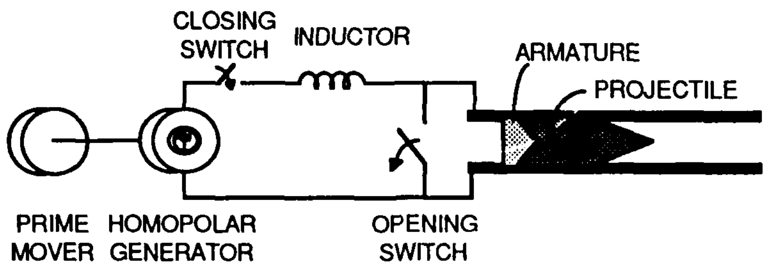
Purpose

The initial five shot series emphasized commissioning the opening switch subsystem, and continued testing of the 620 gram copper-fiber solid armatures designed earlier. This test series was completed without teardown. The ongoing second five shot series makes use of the HPG–inductor–opening switch system, at its maximum 30 MJ, 1.3 MA performance levels to conduct high current testing of solid armatures.

Test Results

The 50-mm square-bore railgun experiments revolve around the use of a shortened (2.65 m) version of the original 50-mm square-bore EMACK barrel. Its purposes were twofold in nature. In the initial five shot series, the emphasis was on commissioning the opening switch subsystem, while, at the same time, continuing testing of the copper-fiber solid armatures designed earlier. Correspondingly, current levels were increased in a conservative fashion from shot to shot. The second five shot group, currently underway, is enabling the use of the HPG-inductor-opening switch system to its fullest capabilities to conduct high current testing of the fiber armatures.

50-mm Square Bore Railgun
Figure 5



Schematic
Figure 6

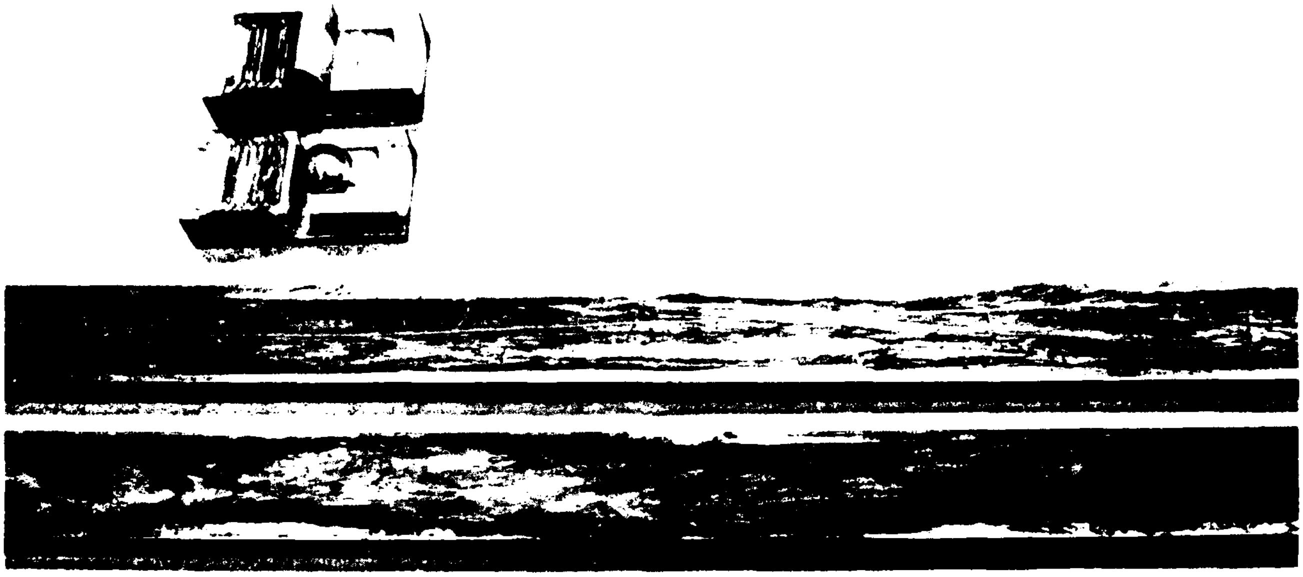
In order to ensure that the opening switch and release mechanism functioned reliably, the first series of tests proceeded in a conservative fashion. For the first two shots the discharge currents were set such that the HPG's $\int I^2(t)dt$ limit would not be exceeded should the rail switch fail to open. The following three shots proceeded in a stepwise fashion to the machine limit of 1.3 MA.

Throughout this series, no work was done to condition the bore of the barrel, with the exception of swabbing with alcohol between firings. The first four shots resulted in no appreciable damage to the barrel, and the muzzle velocity showed only minor variations from the predicted values except in shot #5. On this shot an external arc was struck in the bus work in the vicinity of the switch which resulted in a slightly lower than expected velocity. The shot data is shown in Table 1.

Shot No.	Proj. Mass	Current	Velocity
1	605 g	775 kA	770 m/s
2	598 g	775 kA	800 m/s
3	619 g	975 kA	800 m/s
4	619 g	1020 kA	830 m/s
5	634 g	1300 kA	1260 m/s

Table 1 – 50-mm Square-Bore Railgun Shots 1-5

The results of shot #5 showed substantial discoloration and pitting of both rails (Figure 7). In addition, unusual arc damage was observed outside the bore, between both the breech and muzzle ends of the rails and the barrel containment structure. There was also arcing between the rail switch body and the inductor to



50-mm Square Bore Projectile and Post Shot 5 Rails
Figure 7

switch bus work. While there was no noticeable decrease in system performance, it was important to note that the damage was extensive, and in fact, rendered the barrel unusable without reconditioning. Also, due to the excessive arcing outside the bore, it was found to be impractical to interpret the system voltages to determine whether the values recorded were due to the armature performance or the external arcs.

Following the completion of this series of tests, work was undertaken to recondition the HPG current collection systems. All brush boxes were replaced, and a new all steel rotor installed. The brush boxes were redesigned to incorporate an additional set of finger contacts for each brush, thus doubling the current carrying capability of that portion of the current collection system. Four instrumented brush boxes were installed, with provisions made for measurement of circulating currents within the rotating machine. In addition, the rail switch arc chutes were reconfigured to direct the plasma away from critical areas.

In mid-November, 1987, a second set of experiments on the 50-mm square-bore railgun was begun. As the opening switch had been proven to operate reliably at megampere current levels, it was unnecessary to be as conservative in choosing current levels for these tests. The shot data is shown in Table 2.

In all cases, the muzzle voltages were kept below 30 V, and minimal rail damage was observed. Once again, no attention was paid to the barrel between shots other than a thorough swabbing and inspection.

Shot No.	Proj. Mass	Current	Velocity
6	620 g	700 kA	600 m/s
7	620 g	1125 kA	1066 m/s
8	620 g	1100 kA	1000 m/s
9*	610 g	1300 kA	~1300 m/s
10*	610 g	1300 kA	~1300 m/s

(*Predicted values pending completion of testing)

Table 2 – 50-mm Square-Bore Railgun Shots 6–10

Conclusion

The HPG-inductor-switch system operated properly. The 350-gram restrained fiber armatures performed well doing relatively little damage to the rail surfaces except in individual shots where obvious failures occurred. In prior year low energy tests with 150-gram unrestrained copper fiber armatures, the recovered armatures showed extensive melting and did severe damage to the rails especially in the vicinity of the breech. When the same test was performed on the larger armature all the fibers were recovered and exhibited no signs of melting. Flash x-ray photographs of the larger projectiles in flight indicate no loss of fibers (Figure 8).

Plans

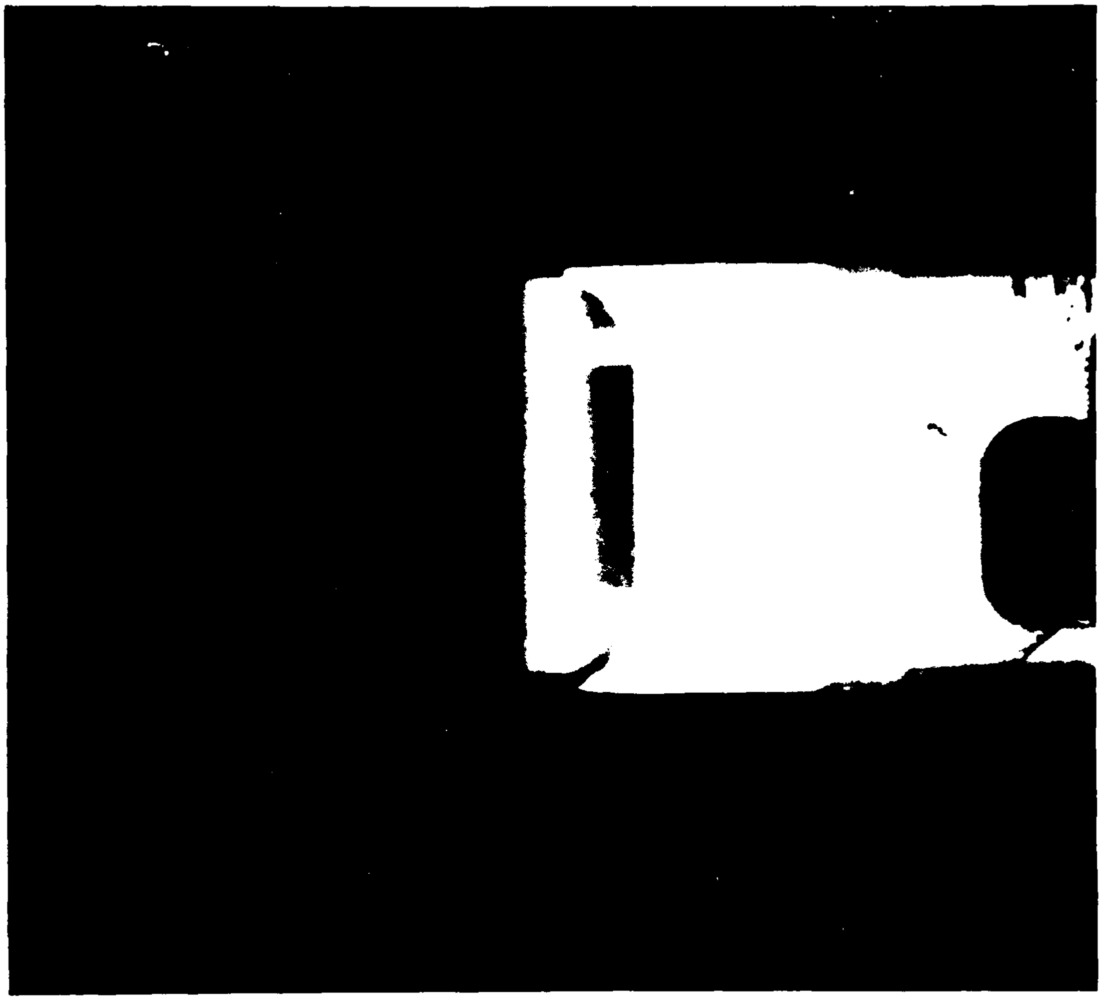
Further testing with decreased amounts of fibers to reduce parasitic weight is planned. Aluminum-fiber solid armatures instrumented for current distribution, acceleration, and voltage and experimental penetrators are planned for future shots with 50-mm square bore railgun. A reduction in bore size to 40 mm is relatively straight-forward with a bolt-together gun like this one and would permit launching lighter projectiles at velocities up to 2.5 km/sec

20-mm Round-Bore Railgun

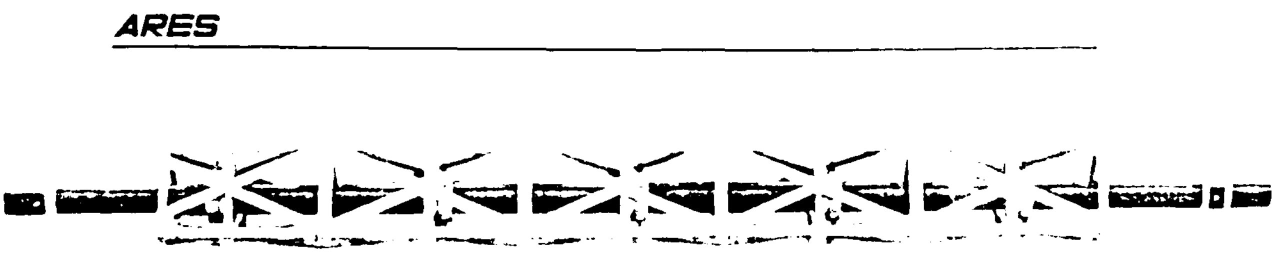
Characteristics

The 20-mm round-bore railgun (Figure 9) is a 4 meter long composite railgun with oxygen-free extruded copper rails cast in an aluminum oxide-cycloaliphatic epoxy matrix dielectric and an outer wrap of carbon fiber/epoxy. The barrel cross-section is shown in Figure 10.

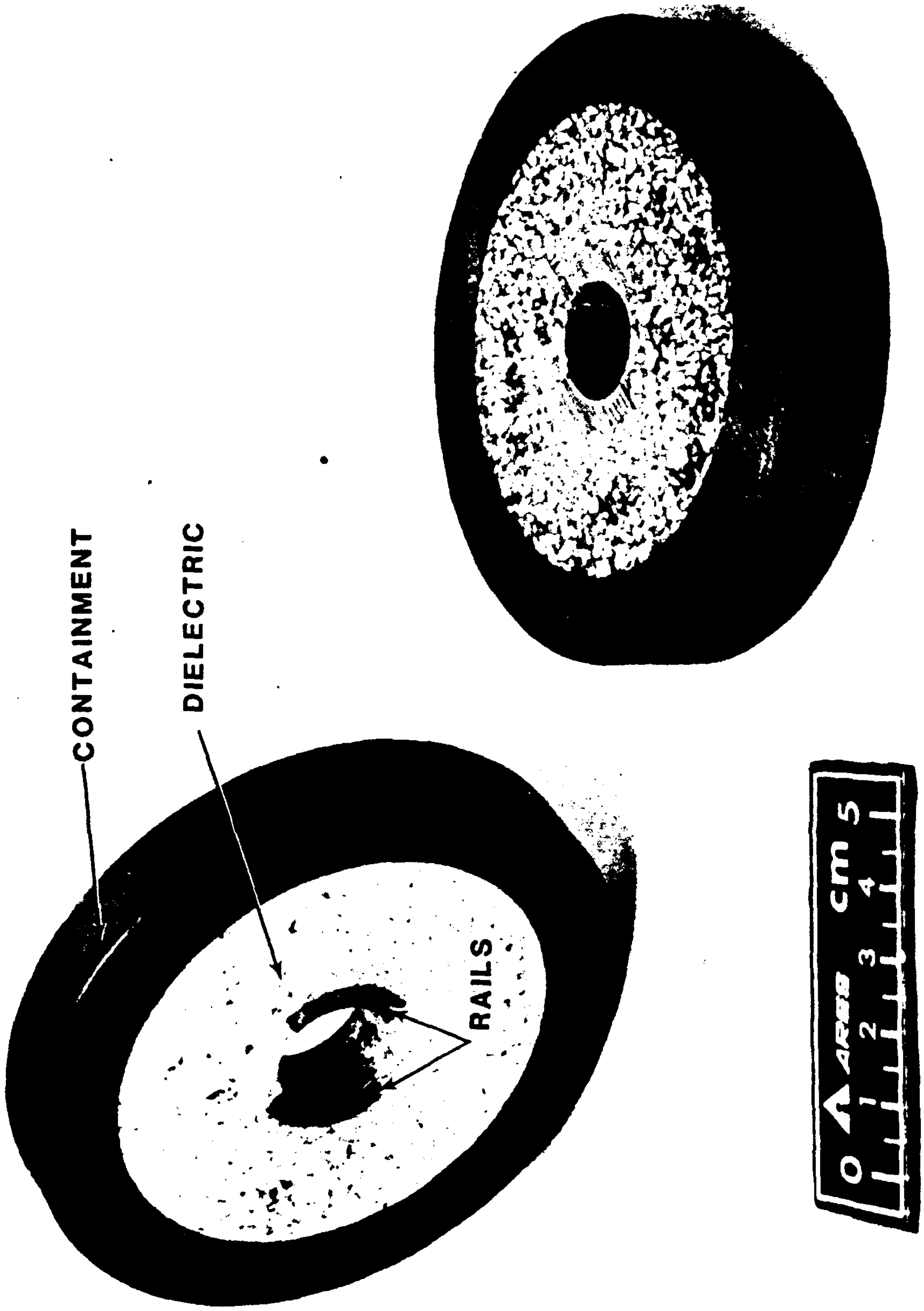
Due to the high expected velocity of 5 km/sec, the slower rail switch will be replaced with an explosive opening switch designed by the Naval Research Laboratory (NRL). Two other NRL explosive switches will be incorporated, one to crowbar the muzzle energy and one to switch a dissipating resistor into the circuit after a maximum time to protect the HPG.



Flash X-Ray of 50-mm Square Bore Projectile in Flight
Figure 8



20-mm Round Bore Composite Railgun
Figure 9



20-mm Round Bore Railgun Cross-section
Figure 10

Purpose

The 20-mm round-bore railgun program has resulted in the manufacture of four 0.4-m long and two 4-m long composite railgun barrels by ARES, Inc. Intended for plasma drive, the barrels were designed to withstand a peak bore pressure of 10 kbar and to minimize rail deflection by maintaining rigid rail backings. The cast dielectric eliminates plasma leakage paths often occuring with bolt-together barrels and reduces difficult machining operation.

The composite barrel offers major advantages for the electromagnetic gun development:

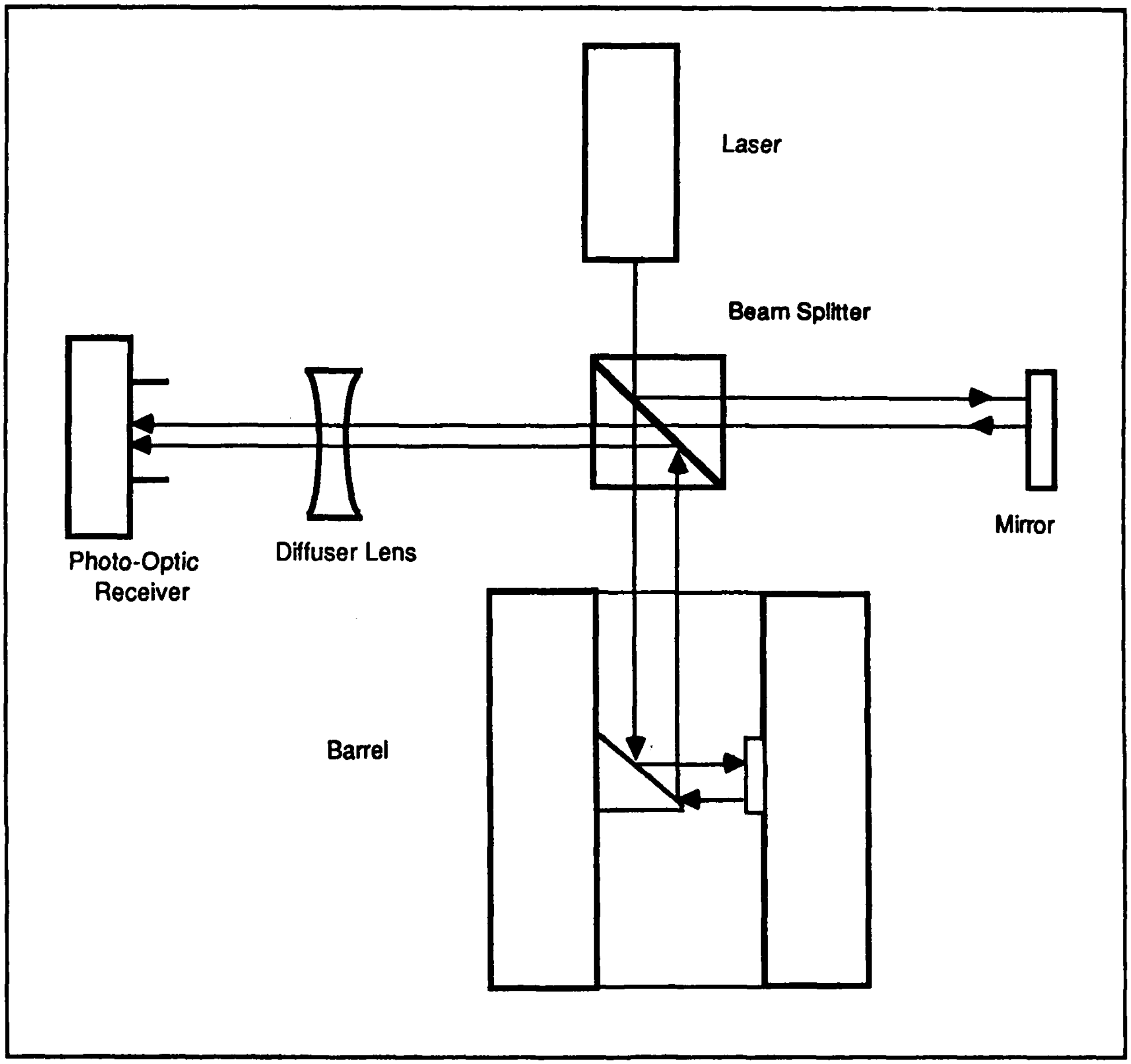
1. The weight is low. A composite barrel is typically a factor of four lighter than a bolt-together one for the same performance.
2. The preload is uniform, leading to a highly efficient structure capable of withstanding the high bore pressures.
3. Reliability is high and no on-line maintenance is required.

Test Results

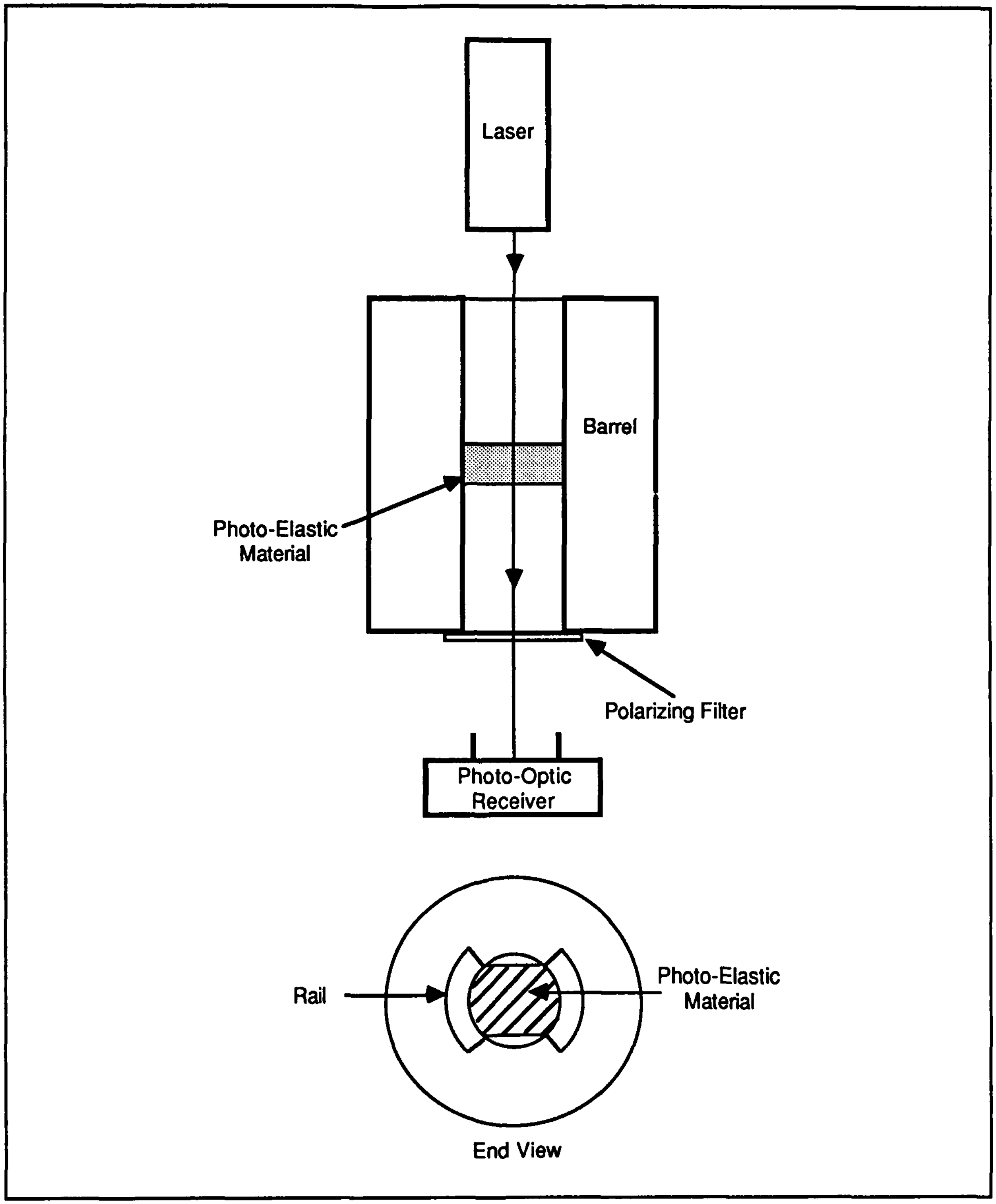
Initial tests were done with 0.4-m short sections of barrel in order to determine experimentally the failure mode to be expected of the 4 meter long barrel. Short barrels with minor variations in the dielectric and end winding materials were manufactured so the barrel material design for the full length barrel could be optimized. These tests were run on the CAPSTAR test stand, five 50 kJ capacitor banks charged to a maximum of 8 KV. Pulse transformers boosted the current output to ~1 MA. Initial tests were conducted as planned; simply pulsing the short barrels without projectiles, ultimately with as a high a current as possible, to test for structural and electrical integrity.

A Michaelson interferometer (Figure 11) was designed and built for the purpose of determining the dynamic behavior of the structure that comprises a railgun bore. While the interferometer produced accurate, repeatable results at relatively low currents, it proved to be sensitive to the mechanical shock and vibrations accompanying a 350 kA discharge. Efforts were made to lessen the sensitivity and to isolate the measurment system from the source of the disturbance. However, the interferometer was found to be unworkable and a measurment system less prone to vibration was developed To solve the problem, a photoelastic material was pressed in between the rails and a polarized neon laser was shone through the material (Figure 12). As the rails expanded, the photoelastic relaxed. As a result of the expansion of the photoelastic material, a fringe pattern associated with the expansion of the bore is produced.

Two of the short 20-mm barrels were destroyed in test. The first experienced a 6.4 mm stretching of the rails in the muzzle area after having the



Interferometer Test
Figure 11



Photoelastic Test
Figure 12

original muzzle fuse replaced with a solid shorting ring. The shorting ring was added in an effort to reduce the shock wave and flash of light experienced by the optical rail deflection measurment apparatus. The effect of the magnetic field near the muzzle reacted with the shorting ring and resulted in an attempt to accelerate the copper ring in the direction of the bore axis. At 490 kA this force stretched the rails 6.4 mm and broke the epoxy-aluminum oxide rail backing into several pieces. This then allowed the rails to bow apart in the vicinity of the broken dielectric (Figure 13).

The second short barrel was used to accelerate a simple polycarbonate projectile to as high a velocity as possible with the relatively low energy and current available with the 250 kJ capacitor energy. In spite of proper torquing, a blind hole, a long bolt, and the absence of a washer at the breech connection resulted in a loose connection between the breech plate tabs and the barrel breech input tabs. Most of energy was dissipated in a significant arc which damaged the barrel breech and the test stand. The current profile and the acceleration distance suggested a final velocity of only 90 m/s.

Each barrel failure occurred at areas of the barrel expected to be the weakest, especially in the radial direction. Structural failure occurred at either end of the barrels where composite windings are nonexistent. A future barrel of similar design would benefit from a change in the positioning of the current tabs so that the composite windings would not have to be interrupted at the ends of the barrel.

Conclusion

The rail deflection (total bore expansion) due to electromagnetic repulsion forces between the rails was measured to be 0.008382 mm at 480 kA. Such a small amount of bore expansion reduces the radial compliance required of the projectile for proper sealing of the plasma. External axial and radial supports will be used with the 4-meter long barrel to compensate for structural design limitations discovered through dynamic testing of the short barrels.

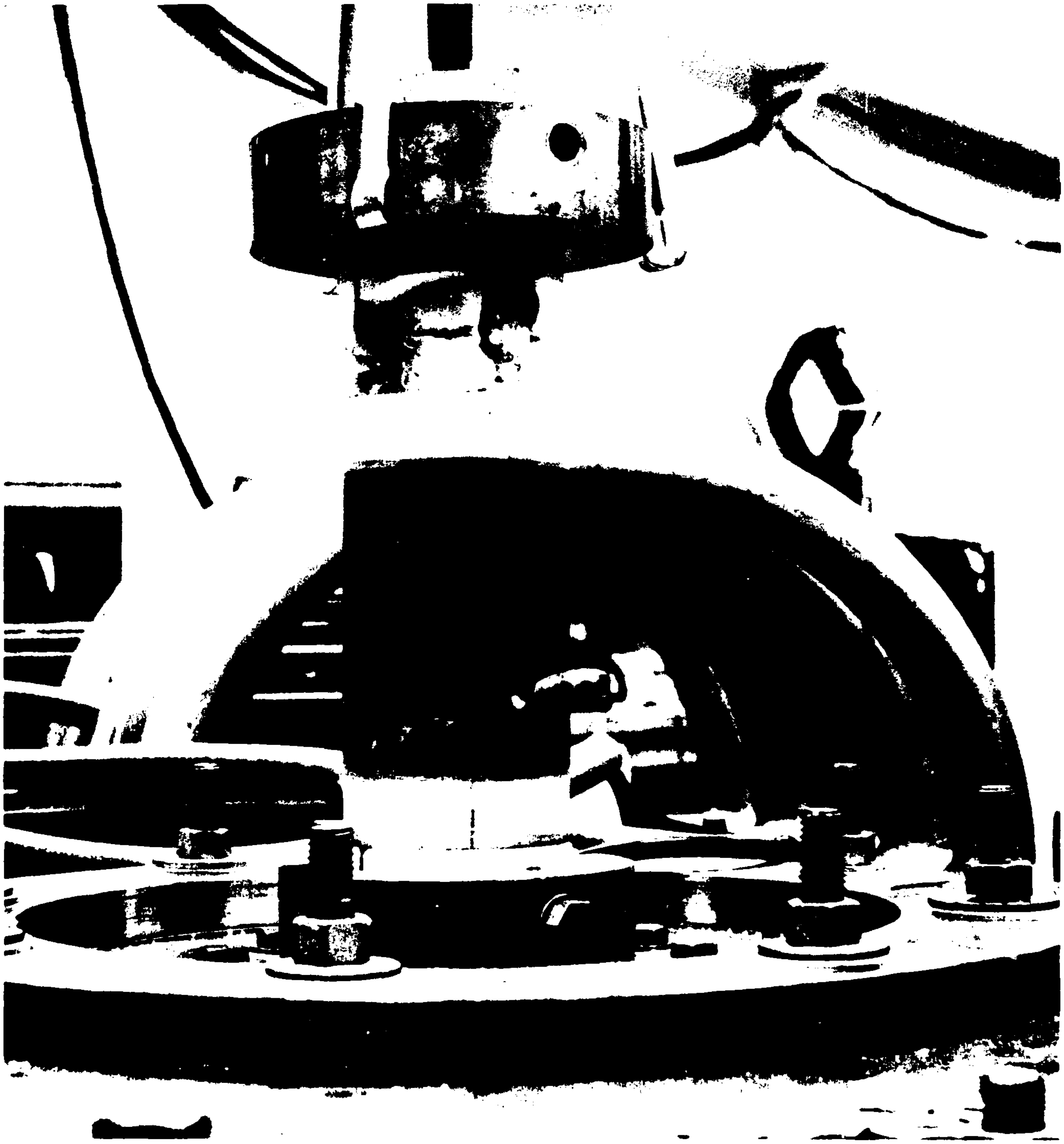
Plans

Test the NRL-designed, explosive switches in August 1989 and if successful proceed with six weeks of hypervelocity tests with the gun.

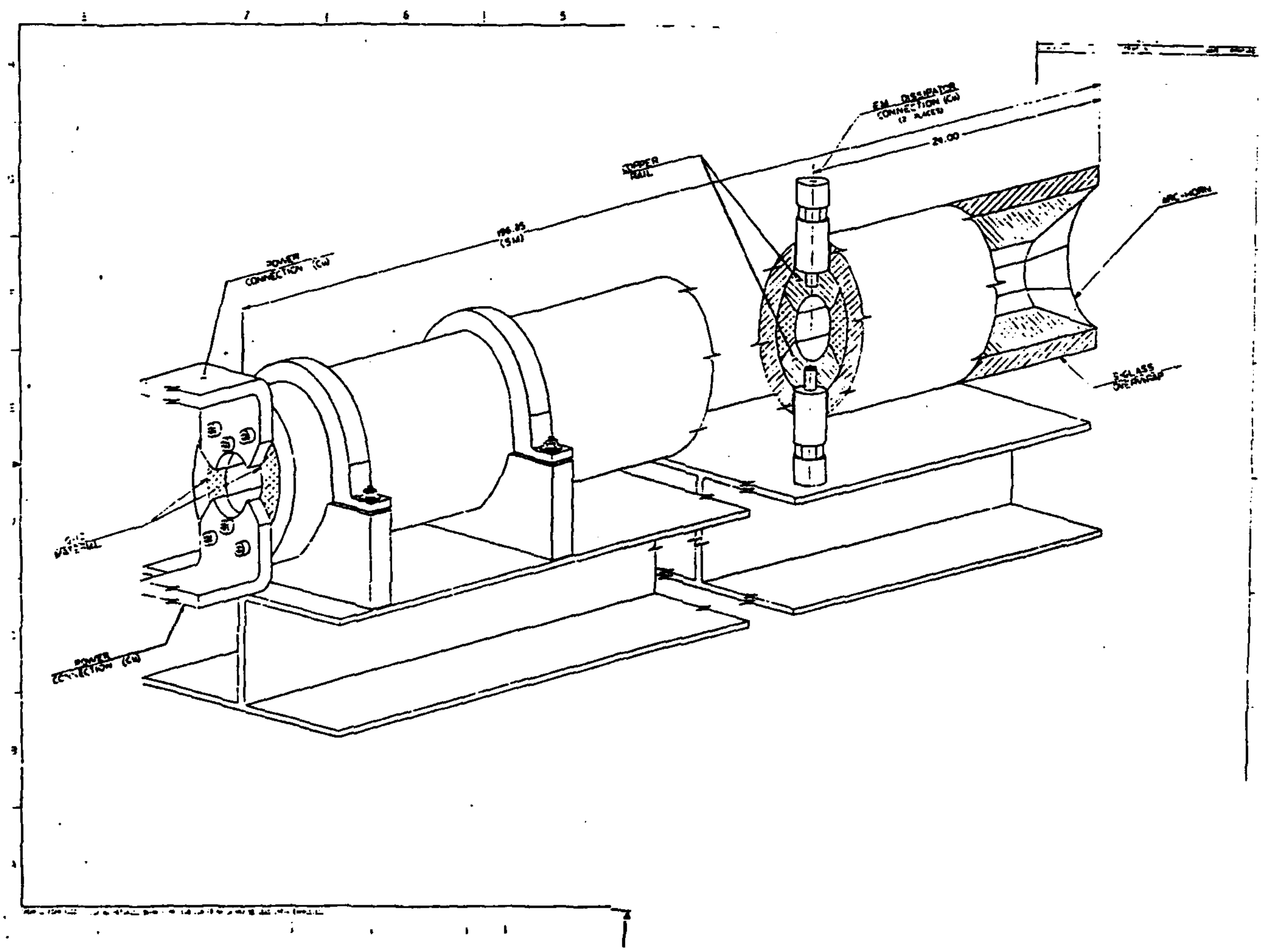
50-mm Round-Bore Railgun

Characteristics

The 50-mm round-bore railgun (Figure 14) is 5 meters long with copper rails backed by G11 fiberglass and structurally supported with a helical winding of E-glass in epoxy plus a layer of longitudinal glass fibers to prevent droop. Two shorter versions 1.2 meters long were fabricated for preliminary tests.



Destructive Test on 20-mm Round Bore Barrel Section
Figure 13



Benét Weapons Lab
50-mm Round Bore Railgun
Figure 14

Purpose

The goals are to develop manufacturing and materials technology for railgun barrels and to develop solid armatures for round-bore railguns (Figure 15). Currently, a test sequence is underway to evaluate armature performance. The 250 kJ capacitor power source is serving as a 500 kA peak current supply to the 1.2-meter long barrel for preliminary low energy evaluation of armatures and barrel design. Three types of armatures have been designed and built by IAP, Inc.; Westinghouse, Inc.; and Los Alamos National Laboratory (LANL). The performance of each of these armatures is being evaluated under low velocity conditions prior to firing at full scale velocity with a 5-m long, 50-mm round-bore launcher. Preliminary results indicate that the Westinghouse armature (aluminum wire bundle type) exhibits the lowest voltage drop (<20 Volts) of the three types being evaluated. So far, it is the most efficient and least damaging of the three types.

Test Results

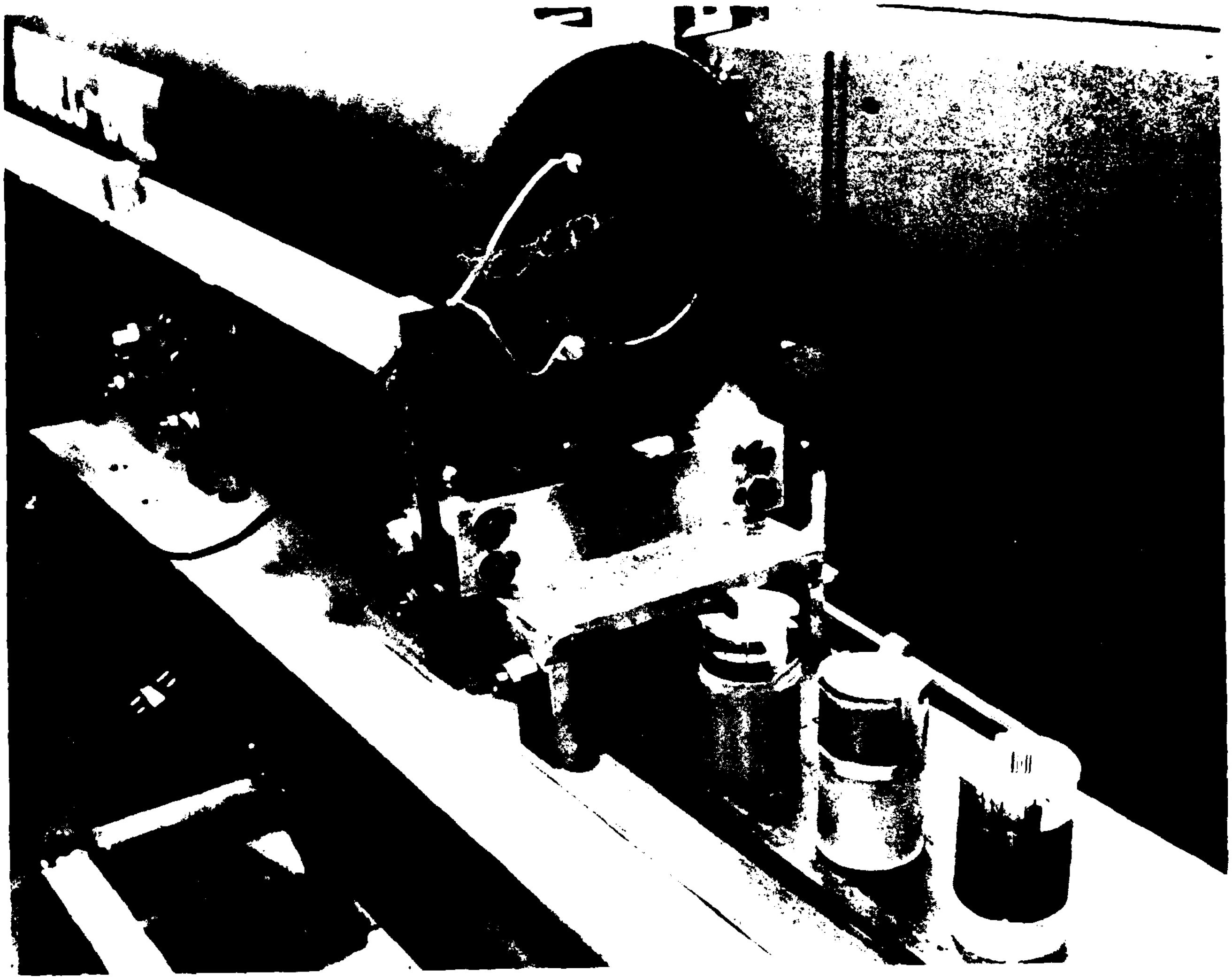
A series of 12 shots has been fired on the first prototype short barrel. One final shot remains to be done in order to fairly evaluate the competing projectile concepts. The development of a consistent experiment required the continuous fine tuning and improvements of the diagnostic set-up during the first 7 shots and their data, therefore, are not presented. A gas injector was used to start projectile motion. A set-back switch in the projectile triggered the capacitor banks after 10 mm of travel. In addition to the set-back switch, the projectiles carried an accelerometer and contact voltage sensors. The wires for these sensors were led from the projectile out the muzzle of the gun. The experimental data used to evaluate relative performance is contained in Table 3. Appendix A contains additional data from Shot #12. Accelerometer, contact voltage sensors, breech voltage monitor, and photonic sensor (for measurements of barrel movement) did not yield comprehensible results.

Shot No.	Proj. Type	Proj. Mass	Current	Muzzle Voltage	Velocity
8	IAP	278 g	500 kA	30 V	160 m/s
9	IAP	299 g	575 kA	60 V	145 m/s
10	LANL	304 g	561 kA	50 V	100 m/s
11	WEC	360 g	490 kA	3 V	84 m/s
12	WEC	429 g	528 kA	8 V	75 m/s
13*	IAP	300 g	550 kA	50 V	150 m/s

(*Predicted values pending completion of testing)

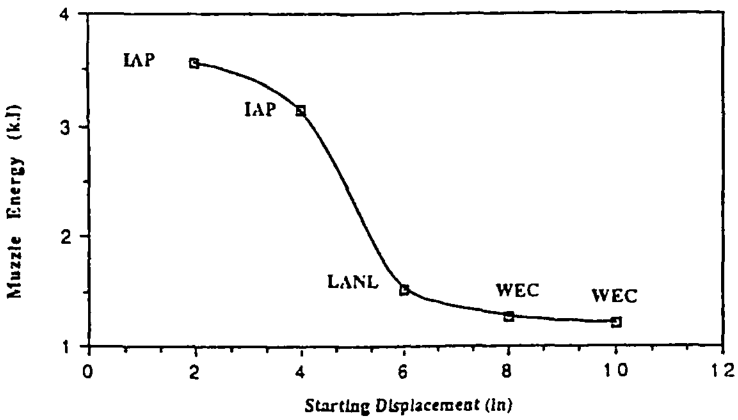
Table 3 - 50-mm Round-Bore Railgun Shots 8-13

The rail surfaces sustained the most damage from arcing at the armature starting positions (Figure 16), where highest current occurs and the projectile is moving slowest. After shot #9, the starting position of armature was moved 50 mm further down the barrel for each shot in order to avoid the previously damaged copper rail surfaces to provide good starting contact. Unfortunately, moving the armature starting position away from the breech increased initial barrel inductance lowering the initial current. The impact of this is reflected in the relationship between the muzzle kinetic energy of projectile and starting displacement plotted in Graph 1.



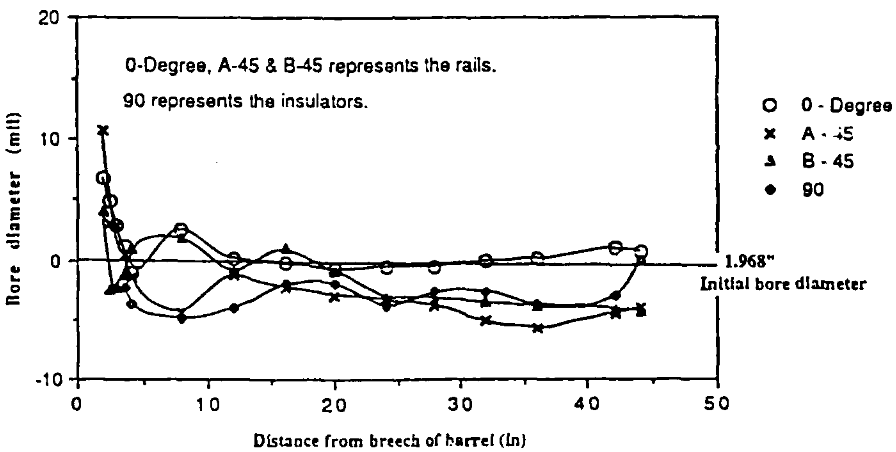
50-mm Round Bore Barrel with LANL, Westinghouse, and IAP Projectiles
Figure 15

50-mm Round Bore Breech Damage after Shot #8
Figure 16



GRAPH 1

The bore diameter was measured along the length after each shot. Graph 2, measured after shot #12, shows that the bore diameter has experienced permanent deflections throughout the length of the barrel. The bore diameter deflection is due to the electromagnetic repulsive forces between the rails during projectile launching and reflects the lack of stiffness and stability of this construction technique. The large apparent deflections at the breech are actually the projectle forcing cone.



GRAPH 2

In order to determine experimentally the dynamic behavior of the barrel during projectile launching, a photonic device was installed at the breech for measuring the bore expansions. The test results obtained so far have proved to be unreliable due to the mechanical shock and vibration accompanying the firing. Further investigation of how to isolate the mechanical shock and vibration will be implemented on prototype barrel #2.

A pressure transducer was installed before the breech of the barrel to determine the pressure distribution of the injector valve and also the injection velocity required to overcome the armature static friction.

Conclusion

The LANL design broke up during launch and has been eliminated from contention. As of shot #12, the Westinghouse projectile armatures appear superior to the IAP designs. They exhibited muzzle voltages below 10 V indicating good sliding contact and they did the least damage to the gun bore in comparison to the others. Armature damage shown in Figures 17 &18 is less critical as they are envisioned to be part of discarding sabots. The maximum rail deflection due to the electromagnetic repulsion forces between the rails was measured to be about 0.76 mm approximately 50 mm from the breech. This was to be expected as this was the armature starting position for the first eight shots. Bore expansion like this requires a compliant armature to maintain good contact or severe arcing will occur.

Plans

Completion of the first prototype testing is planned for January 1989. This will be followed by tests on a second short prototype containing jointed rails (necessary in the longer guns) and a series of ten shots each on two 5-meter barrels.

10-mm Material Test Railgun

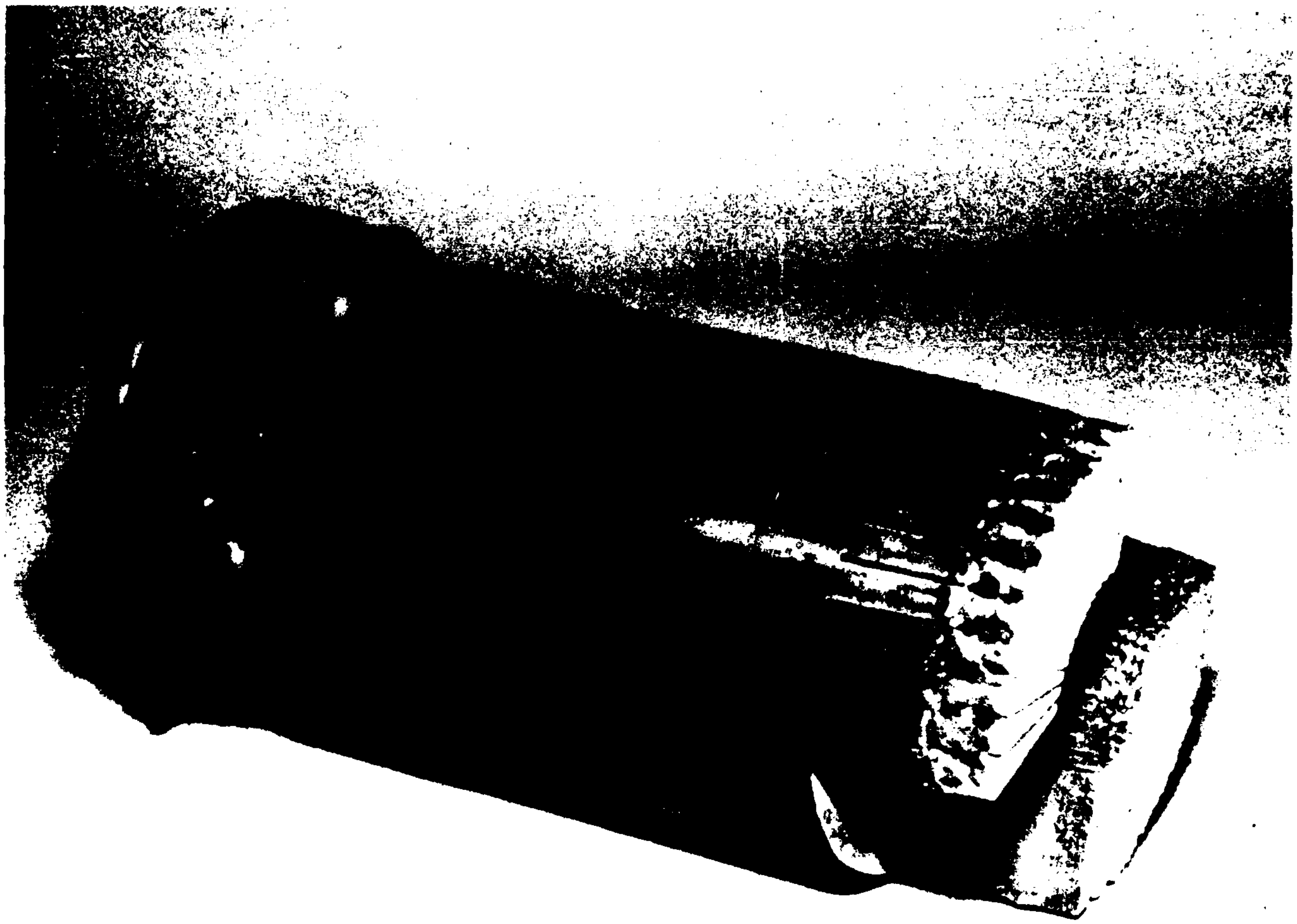
Characteristics

The 10-mm material test railgun (MTR) is a 0.61 meter long, bolt-together, square-bore railgun (Figure 19). The copper rails are backed by G11 and steel plates. The insulators can be either polycarbonate or G11. This railgun was designed by General Dynamics for the Air Force to conduct plasma drive experiments and a new barrel was obtained from the Air Force for ARDEC's own experiments. The MTR has several ports spaced five centimeters apart in the side plates for B-dot probes and ports located in the top and bottom plates for probes. All of these access holes end in the insulators do not reach the bore or back of the rails. The original rails and insulators supplied with the gun were of standard first generation materials; copper for rails and polycarbonate for insulators.

One Maxwell 50-kilojoule capacitor bank was used as the power source for the MTR and one 17.4-μH solenoid inductor served as the pulse shaping element. Ignitrons initiate the discharge of the capacitors within the bank and a crowbar ignitron bypasses the capacitors shortly after peak current, thereby isolating them from the rest of the railgun/inductor circuit. The ignitrons are an integral part of the capacitor bank and the delay for the crowbar is adjustable.

A compressed gas injector is usually used with the MTR for tests using plasma armatures in order to reduce bore damage due to the plasma's intense heat and residence time. However, the injector was not used for these tests since the capacitor bank was only available for a limited time. A rag-filled aluminum tube was used to catch the projectiles and an open space of 90 centimeters was left between the muzzle of the gun and the beginning of the catch tube for assorted laser gates and an optical break fiber. Tektronix 390ADs and Nicolet scopes were used to store data from the voltage probes and triggers.

Westinghouse Projectile after Shot #7
Figure 17



IAP Projectile after Shot #8
Figure 18

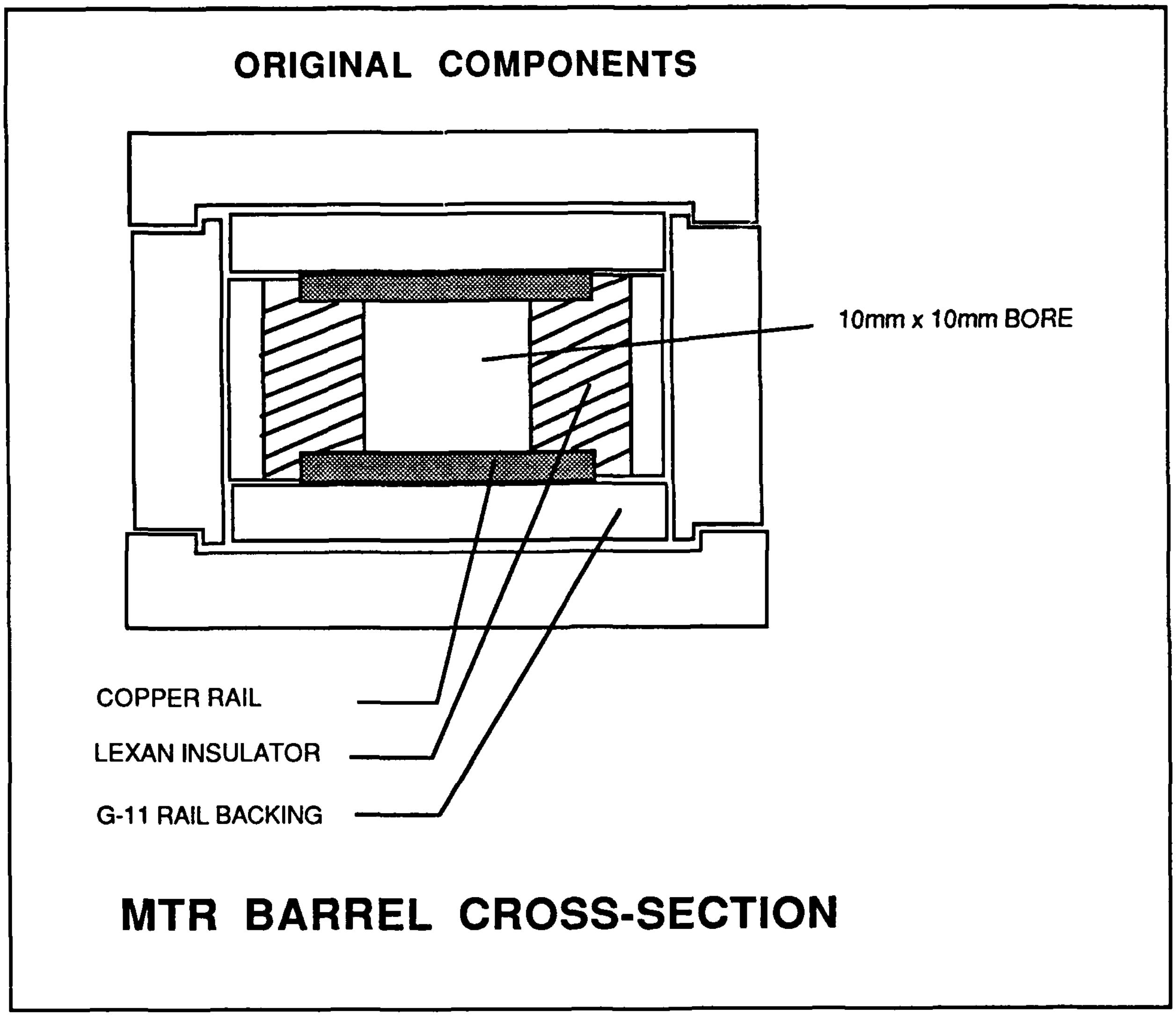


Figure 19

Purpose

The MTR is a small, low energy barrel used for materials testing in a railgun environment. Rails and insulators are easily replaced due to the barrels bolt together construction. A series of nine 10-mm materials test railgun shots were fired in July 1988 in preparation for experiments currently underway with Sparta, Inc. The objective of these shake-down tests was to eliminate any bugs occurring with the instrumentation or power circuit and to ensure that everything was in satisfactory working condition. Fiber optics were tested for use as velocity gates.

Test Results

The barrel has been used with plasma armatures at ARDEC for diagnostic and trigger development. See Appendix B for individual test data.

Projectile/Armature. In each test a plasma was created by inserting a small piece of aluminum foil into the barrel bore. For shots with a polycarbonate projectile, the foil was glued to the back of the projectile with five minute epoxy. The projectile had a loose slide fit and contact of the foil with the rails upon insertion was ensured by a continuity check with a Fluke ohm meter. No attempt was made to keep the plasma from passing around the projectile with a seal or tight fitting projectile. The polycarbonate projectiles all had a mass of 2.4 grams except for shot #7 which was 6.0 grams due to a steel insert within the projectile for x-ray photographs. Shots #6, 8 & 9 launched plasma projectiles. The rest were polycarbonate projectiles. All projectiles were caught in a catch tube loosely filled with rags was used to stop the projectiles. All the polycarbonate projectiles (~100 m/sec) survived intact. Plasma blow-by was evident by the black soot markings on the projectiles sides. The projectile starting position was moved towards the muzzle as tests progressed to avoid jamming the projectile in the breech area, where resolidified copper built up on the rails.

Energy Source. For the first four shots the capacitors were charged to 6 KV. The last five were done at 8 KV. This resulted in peak currents of 35 KA and 47 KA respectively with two exceptions. In shot #1 (6 KV) the peak current was only 11 KA. Instead of the armature vaporizing (the foil was undamaged after the capacitor discharge) and becoming a plasma, an arc occurred at the muzzle which appears to have jumped from one voltage connector to the other. This resulted in a peak current of only 11 KA. Each connector was screwed into the end of the rails, one in the top and the other in the bottom rail. The connectors were not any closer to each other than the rails were but the sharp edges and points on the fork-type connectors may have created a locally high electric field intensity sufficient to cause electrical breakdown at a lower voltage than that required to jump an arc from one rail to the other. This could only have happened if the foil was not in proper contact with the rails. Thereafter, a continuity check was made each time on the rail-foil-rail connection with no further arcing problems.

In shot #6 (8 KV) the peak current was only 37 KA. No cause could be determined.

Diagnostics. Laser driven, fiber optic cables used as break-fibers provided projectile velocities at the muzzle and down range. The optical fibers proved to be more reliable and less susceptible to false triggering by a plasma, smoke or electrical noise than electrical break-wires. However, even the optical break-fibers failed to work flawlessly when exposed to full power at the muzzle of the barrel. The fiber broke in one of the MTR shots where the fiber was intentionally exposed to a severe plasma shock. The fiber was fixed at the muzzle of the barrel and the plasma initiated with a foil placed near the muzzle end, so that the plasma would be near its peak pressure and temperature when it hit the fiber. The high pressure and temperature of the full power plasma shot broke the fiber, indicating that the optical fiber may break prematurely due to plasma blow-by when used as a velocity sensor in plasma drive railguns.

The B-dot probes could not be made to function correctly. They appear to be to sensitive for the high voltage, fast transient capacitive energy source.

Conclusion

The shake-down tests were used to recommission the MTR and familiarize the lab personnel, to be involved with the Sparta material tests, with the test set-up and procedures. The capacitor bank worked reliably for all 9 shots. Checking for continuity between the rails and the armature foil ensured a successful ignition of the foil each time.

The fiber optic cables proved to be a useful diagnostic tool. They are essentially immune to electrical noise and the fiber-optic cable can provide a reliable, positive means of detecting the presence of a projectile. They have since been used successfully as velocity gates and x-ray triggers for short 50-mm round-bore experiments. Despite the success of these break-fibers with solid armature railguns, they are susceptible to false triggering when exposed to a plasma shock wave as experienced in a plasma armature railgun. This is not to say, that they cannot be made to work with proper modifications to the fiber, such as insulative wraps or protective tubes.

Plans

The MTR will soon be used to compare solid and plasma armatures with various advanced insulators and rails under a Materials Test Lab contract with Sparta Research. From these tests, it will be learned how well various advanced rails and insulators behave when exposed to the pressures, temperatures, abrasion and ablation of the railgun environment. The results of these tests will be used for the selection of materials for future railgun barrels to be tested at ARDEC.

OVERALL LABORATORY CONCLUSIONS

The two laboratory pulse power supplies and the instrumentation and diagnostic capabilities of the laboratory have been improved.

The 50-mm square bore railgun has shown that dramatic improvements in barrel wear can be achieved by proper armature design.

The short 20-mm round bore railgun barrel tests have given preliminary indications that the composite barrel design will withstand the forces involved in the upcoming 5 km/sec tests.

The 50-mm round bore railgun tests pointed out the difficulties of round-bore solid armature design and the importance of matching barrel stiffness and armature compliance. The initial composite design proved adequate. The stiffer designs should display improved performance in efficiency and barrel life.

FUTURE LABORATORY PLANS

The 50-mm square bore railgun bore will be reduced to 40 mm in order to continue significant solid armature studies at velocities above 2.5 km/sec.

The 20-mm round bore railgun experiment will be completed for valuable information on plasma armatures at velocities near 5 km/sec and explosive switch operation.

Testing of full length 50-mm round bore composite barrels will be conducted to evaluate barrel construction techniques in conjunction with related armature development at Los Alamos National Laboratory.

Continued railgun materials evaluation will be conducted using the 10-mm MTR.

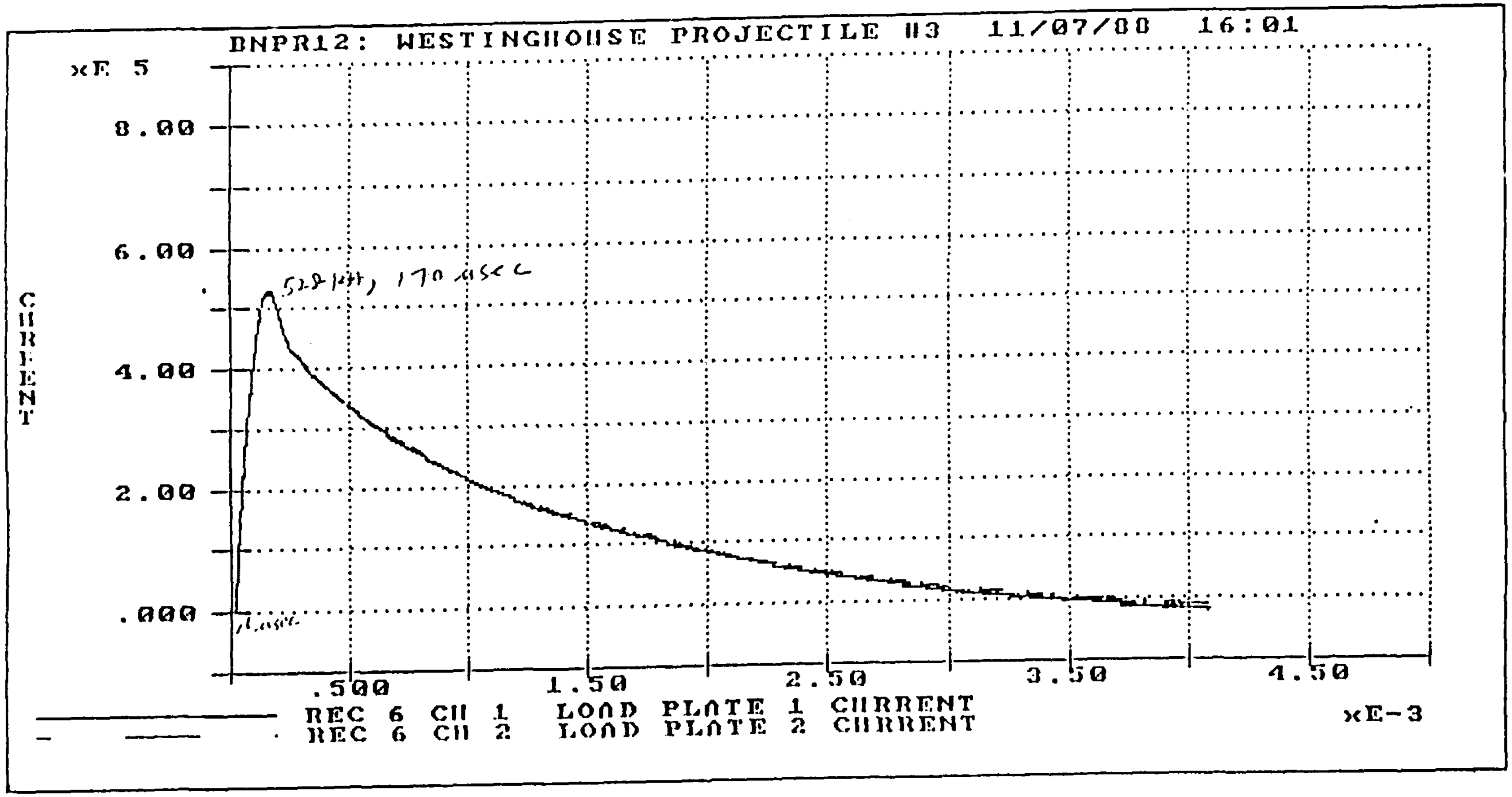
Building 717 preparations for high energy testing will be completed and the 90-mm electrothermal and 120-mm advanced railgun test programs will be initiated.

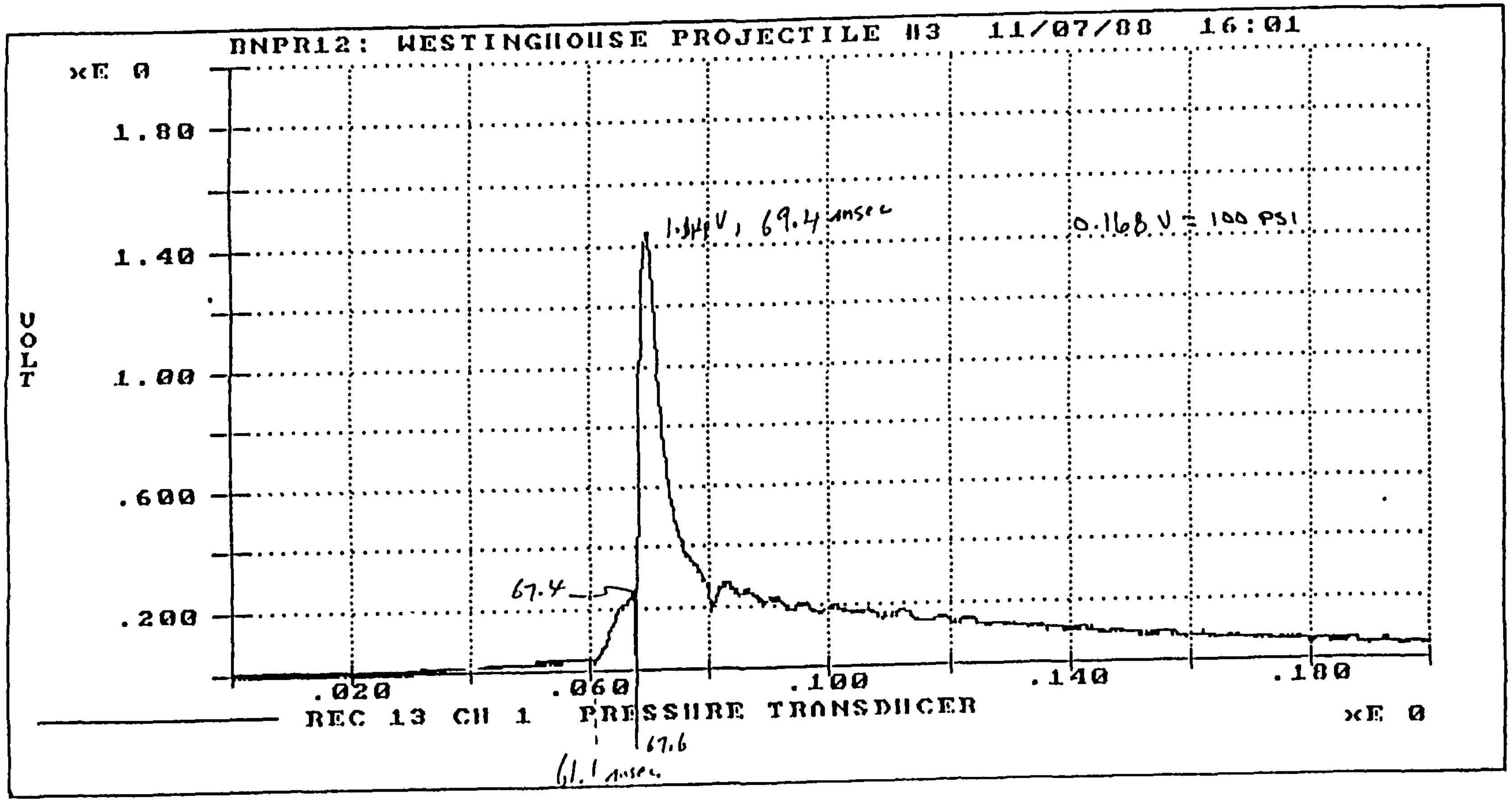
APPENDIX A

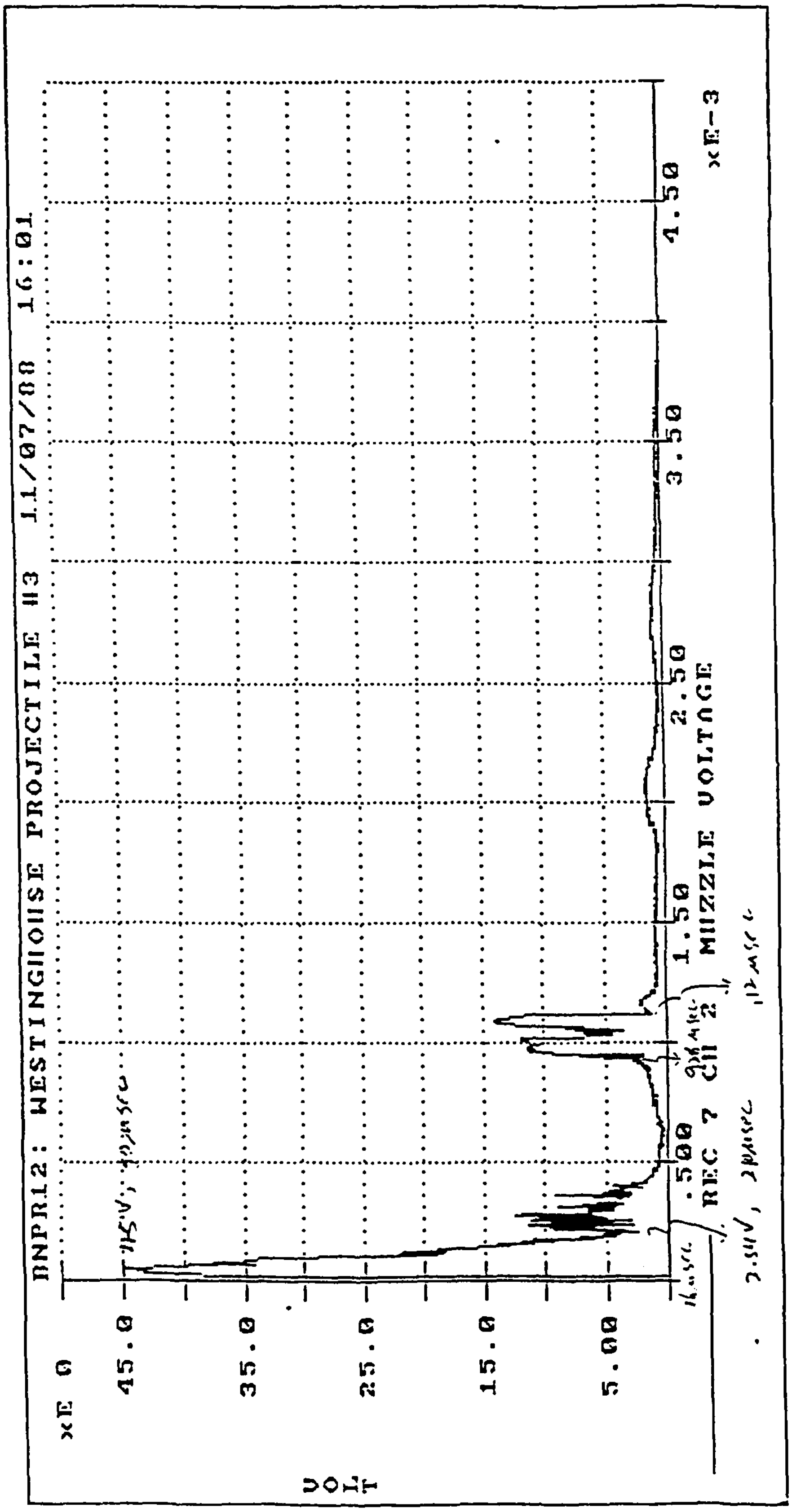
50-mm ROUND-BORE RAILGUN DATA

Summary of 50-mm Round Bore Railgun
Shot #12

Date of Test	07 NOV 88
Armature Type	WESTINGHOUSE (#1)
Projectile Mass	357 grams
Projectile + Package Mass	428.5 grams
Injector	975 psi
Insertion force	210 lbs (@ 10")
Primary Current – Bank 1	92.6 KA
Primary Current – Bank 2	88.2 KA
Primary Current – Bank 3	71.5 KA
Primary Current – Bank 4	84.4 KA
Primary Current – Bank 5	137 KA
Secondary Current	528 KA
Muzzle Voltage	8 V
Muzzle Velocity	75 meters/sec


BNPR12: WESTINGHOUSE PROJECTILE #3 11/07/88 16:01
xE 5
8.00
6.00
4.00
2.00
.000
CURRENT
.500
1.50
2.50
3.50
4.50
xE-3
REC 6 CH 1 LOAD PLATE 1 CURRENT
REC 6 CH 2 LOAD PLATE 2 CURRENT


BNPR12: WESTINGHOUSE PROJECTILE #3 11/07/88 16:01
xE 0
1.80
1.40
1.00
.600
.200
VOLT
.020
.060
.100
.140
.180
REC 13 CH 1 PRESSURE TRANSDUCER
xE 0
1.44V, 69.4 msec
0.168 V = 100 PSI
67.4
67.6
61.1 msec


BNPR12: WESTINGHOUSE PROJECTILE #3 11/07/88 16:01
MUZZLE VOLTAGE
REC 7 CH 2
VOLT
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35.0
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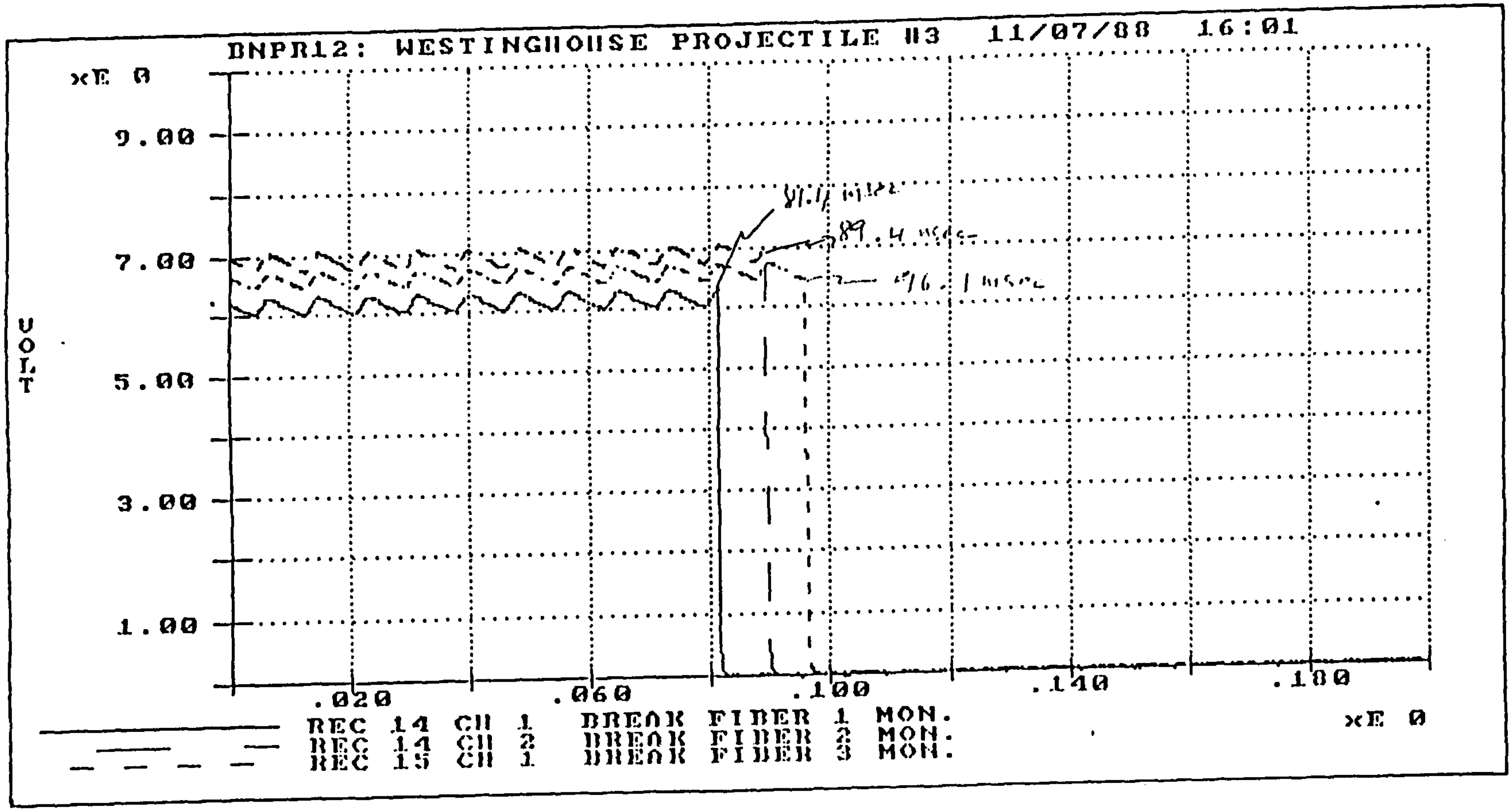
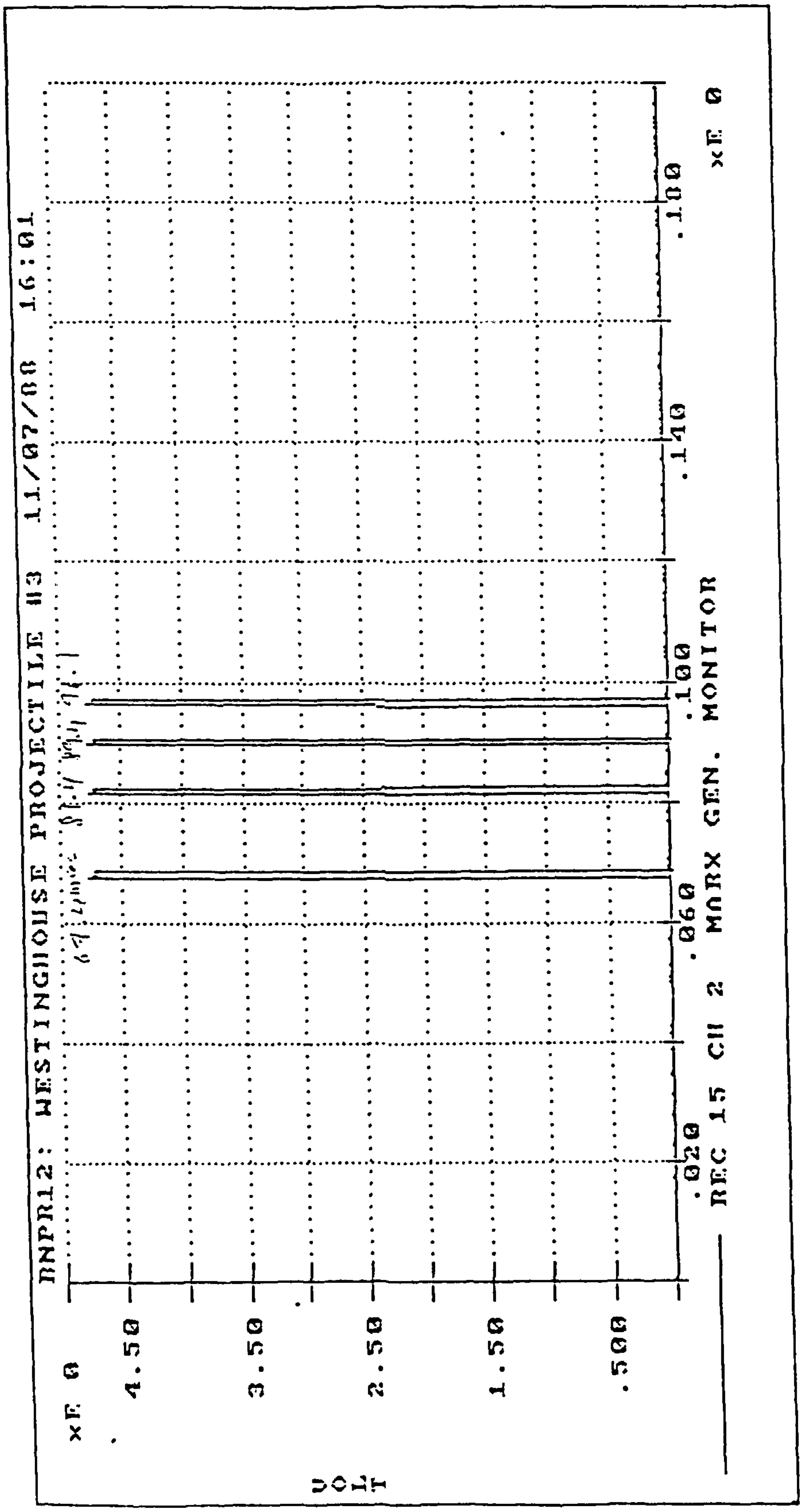
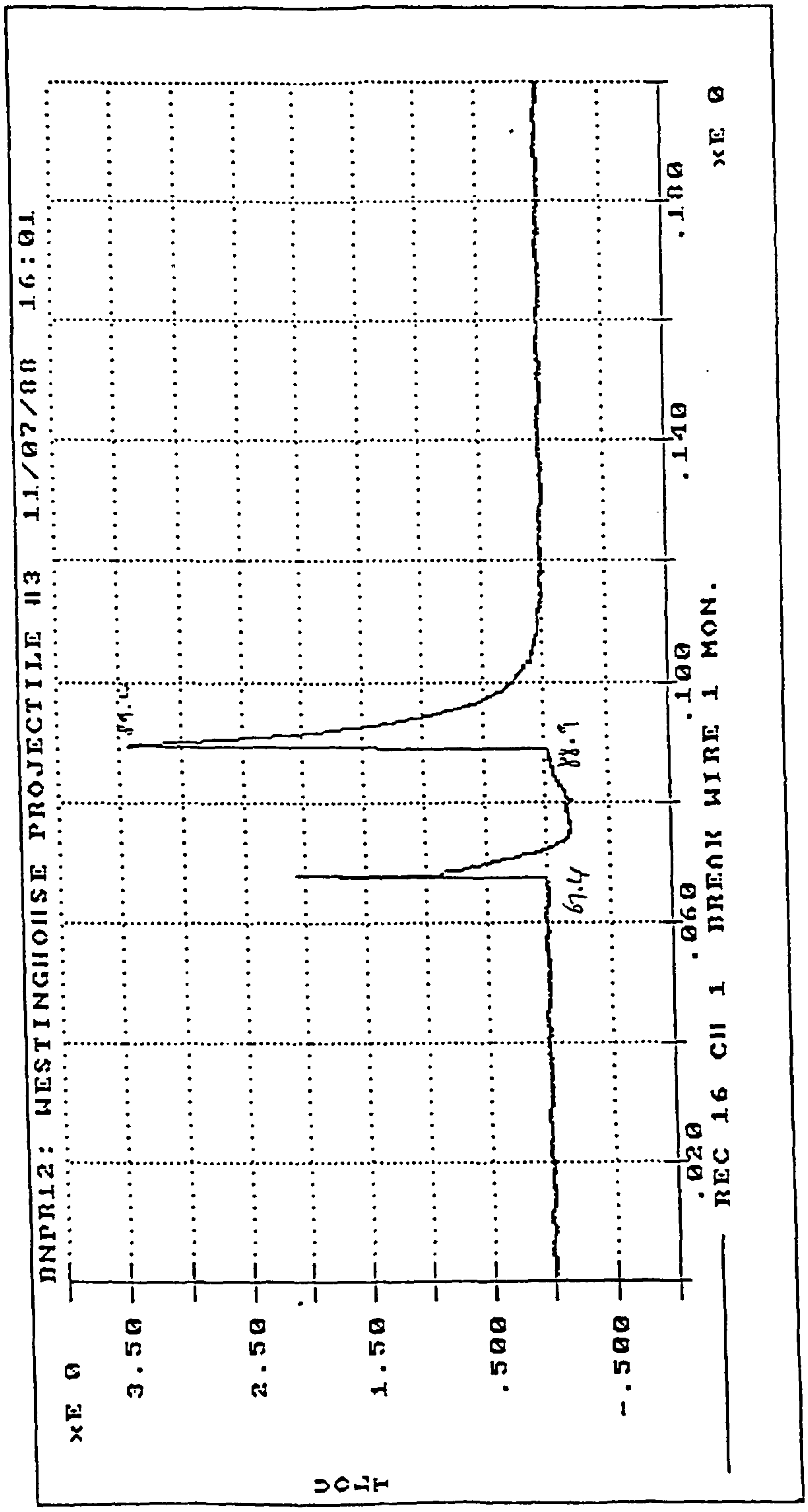
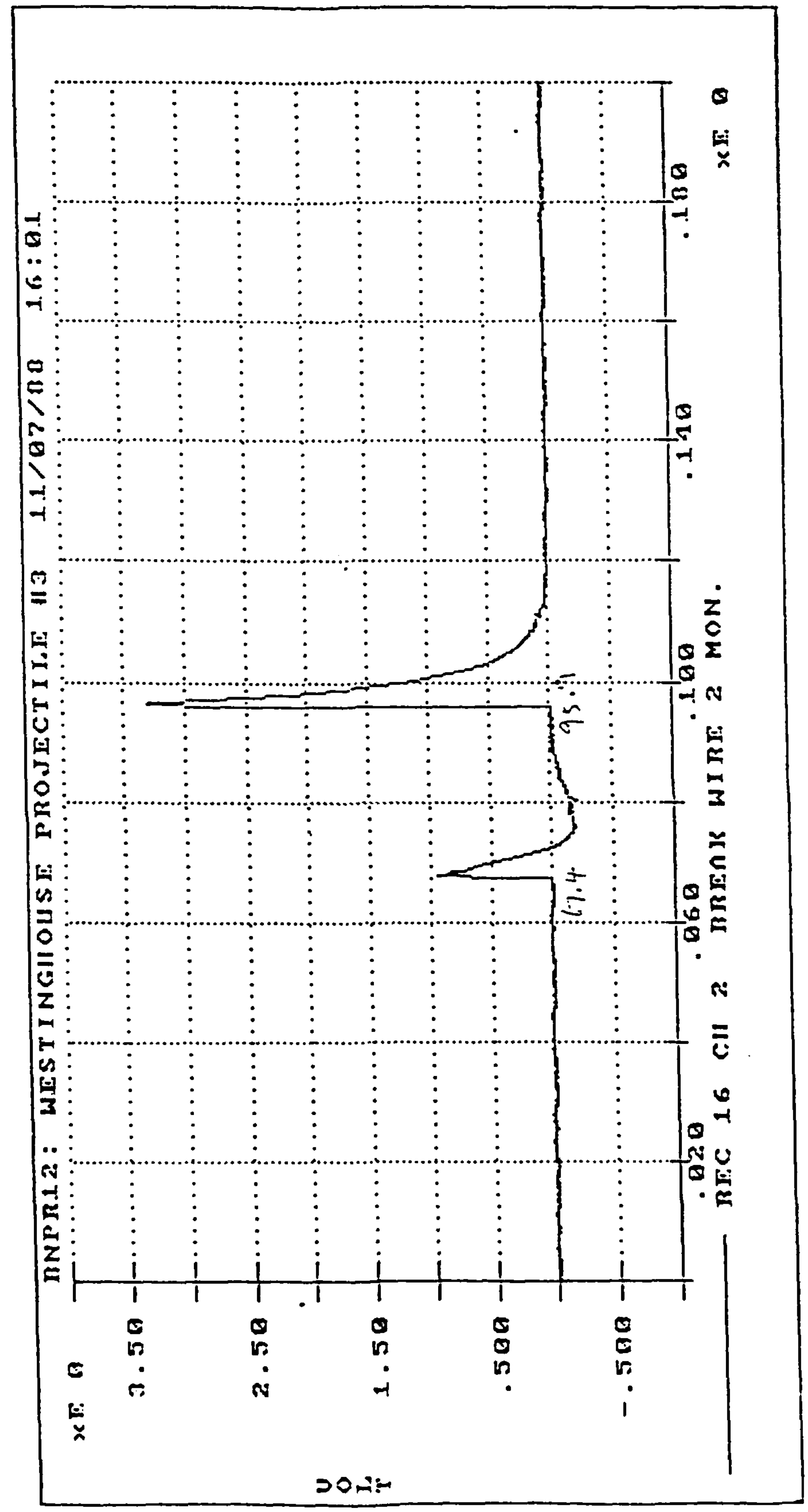
5.00
.500
1.50
2.50
3.50
4.50
xE-3


BNPR12: WESTINGHOUSE PROJECTILE #3 11/07/88 16:01
xE 0
9.00
7.00
5.00
3.00
1.00
VOLT
.020
.060
.100
.140
.180
xE 0
89.4 msec
96.1 msec
REC 14 CH 1 BREAK FIBER 1 MON.
REC 14 CH 2 BREAK FIBER 2 MON.
REC 15 CH 1 BREAK FIBER 3 MON.


BNPR12: WESTINGHOUSE PROJECTILE #3 11/07/88 16:01
REC 15 CH 2 MARX GEN. MONITOR
VOLT
xE 0
4.50
3.50
2.50
1.50
.500
.020
.060
.100
.140
.180
xE 0



BNPR12: WESTINGHOUSE PROJECTILE #3 11/07/88 16:01
VOLT
xE 0
3.50
2.50
1.50
.500
-.500
.020
.060
.100
.140
.180
xE 0
REC 16 CH 1 BREAK WIRE 1 MON.


BNPR12: WESTINGHOUSE PROJECTILE #3 11/07/88 16:01
REC 16 CH 2 BREAK WIRE 2 MON.
.020
.060
.100
.140
.180
xE 0
3.50
2.50
1.50
.500
-.500
xE 0
VOLT
95.1
67.4

APPENDIX B

10-mm MATERIAL TEST RAILGUN DATA

Summary of FLINT Shots

Date Of Test	7/15/88 Shot #1	7/15/88 Shot #2	7/21/88 Shot #3	7/21/88 Shot #4	7/22/88 Shot #5	7/25/88 Shot #6
Armature Type	Al. Plasma	Al. Plasma	Al. Plasma	Al. Plasma	Al. Plasma	Al. Plasma
Projectile Type	Lexan	Lexan	Lexan	Lexan	Lexan	Plasma
Proj Mass / Arm Mass (g)	2.4 / 0.1	2.4 / 0.1	2.4 / 0.1	2.4 / 0.1	2.4 / 0.1	- / 0.2
Injector	no	no	no	no	no	no
Insertion Force (lbs)	0	0	0	0	0	0
Cap Bank #3- (kV, kA)	6 , 11	6 , 34	6 , 35	6 , 35	8 , 46	8 , 37
Breech Voltage (V)	± 1000 pk	NA	NG	NG	12	NA
Muzzle Voltage (V)	± 1000 pk	NA	80	120	300	NA
B-Dots 1,2,3,4 (msec)	NA	1-3 picked up crowbar, 4 *	1-3 picked up crowbar spike	1-4 picked up crowbar spike	*	*
Optical Break-Fiber (msec)	NA	NA	7.7	7.8	4.8	disconnected at 7.5 ms
LASER Gate #1 (msec)	NA	NA	triggered by BF at 7.7 ms	11.5	6.6	plasma induced noise
LASER Gate #2 (msec)	NA	NA	triggered by BF at 7.7 ms	11.5	no break signal	plasma induced noise
Muzz Vel (m/s)/ Kin. Ener. (J)	No proj exit	NA	68 / 5.8	82 / 8.4	167 / 35	NA

Shot #1 resulted in no acceleration of projectile.

* Unreadable due to electrical noise

Summary of FLINT Shots

Date Of Test	7/25/88 **Shot #7**	7/26/88 **Shot #8**	7/26/88 **Shot #9**	Shot #10	Shot #11	Shot #12
Armature Type	Al. Plasma	Al. Plasma	Al. Plasma			
Projectile Type	Lexan w/.lead	Plasma	Plasma			
Proj Mass / Arm Mass (g)	6.0 / 0.1	/ 0.2	/ 0.2			
Injector	no	no	no			
Insertion Force (lbs)	0	0	0			
Cap Bank #3- (kV, kA)	8 , 47	8 , 47	8 , 48			
Breech Voltage (V)	NA	NA	NA			
Muzzle Voltage (V)	NA	NA	NA			
B-Dots 1,2,3,4 (msec)	*	0.69, 0.73, 0.75, -*	0.32, 0.37, -*, -*			
Optical Break-Fiber (msec)	6.9	0.4-7.7	0.55			
LASER Gate #1 (msec)	4.5	NA	NA			
LASER Gate #2 (msec)	13.1	NA	NA			
Muzz Vel (m/s)/ Kin. Ener. (J)	70 / 14.7	1000 / NA	600 /NA			

* Unreadable due to electrical noise

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